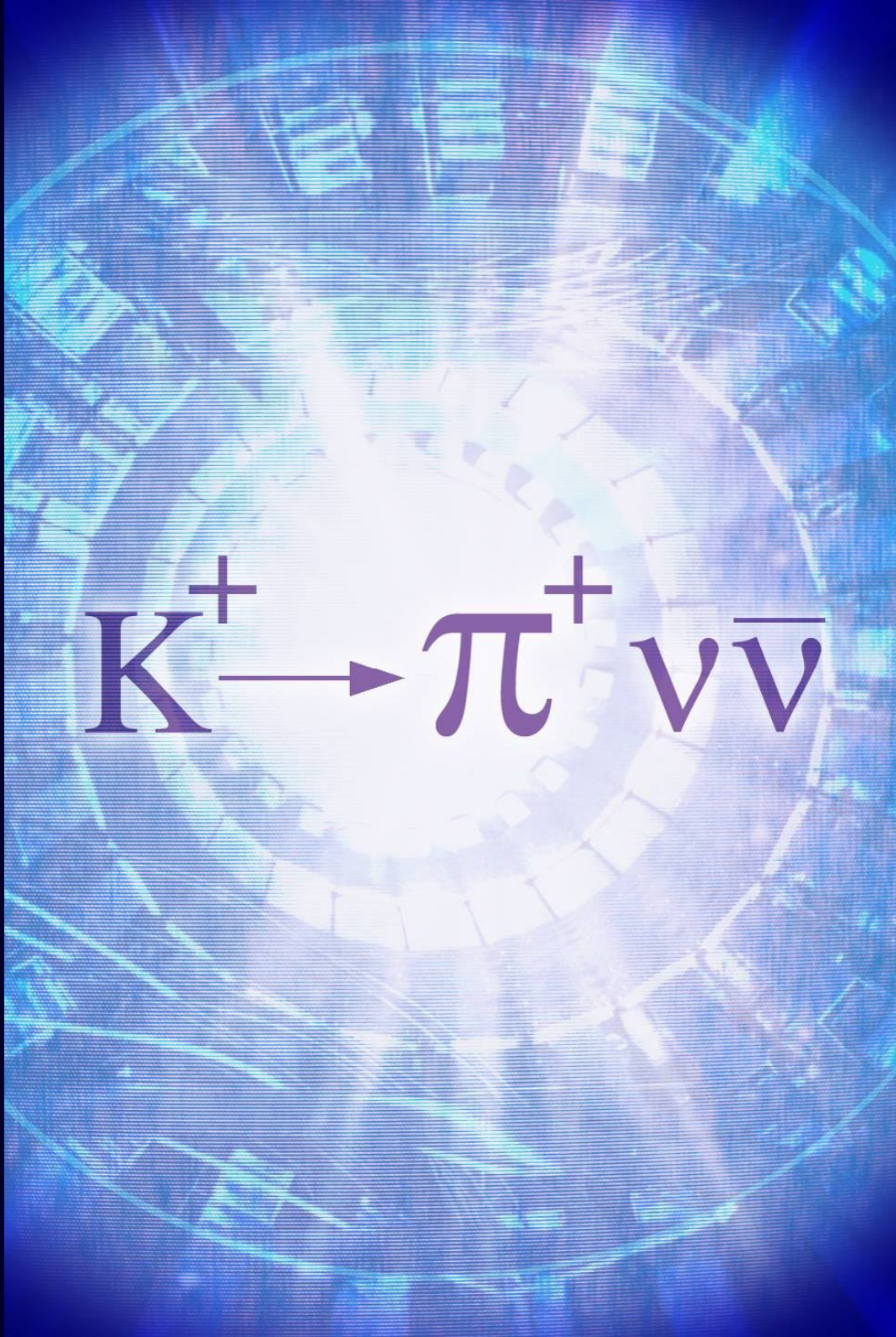


**Final BNL E949  
results on the  
measurement of  
the rare decay**

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

**Joss Ives**

University of the  
Fraser Valley


$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

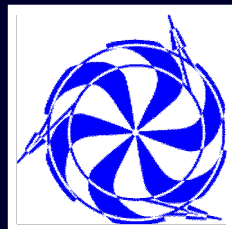


**Final BNL E949  
results on the  
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**Joss Ives**

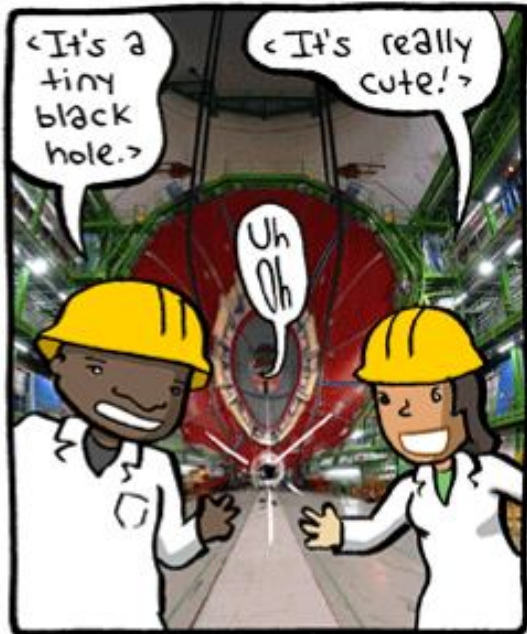
**UBC / TRIUMF**



$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

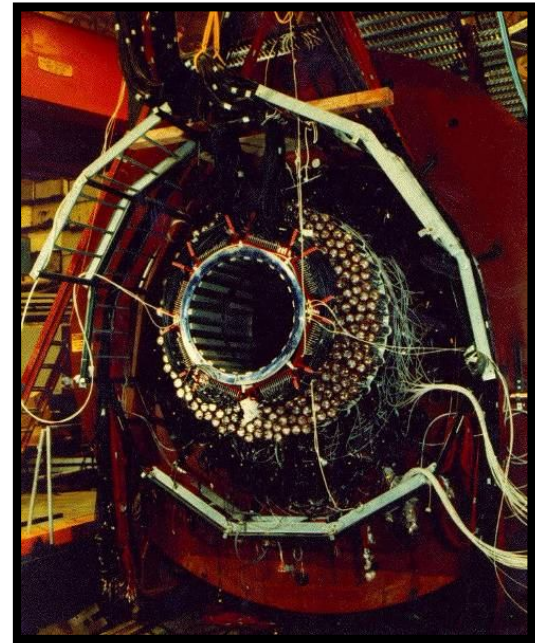
# To find physics beyond the Standard Model, particle physicists try to break the Standard Model

## Energy frontier



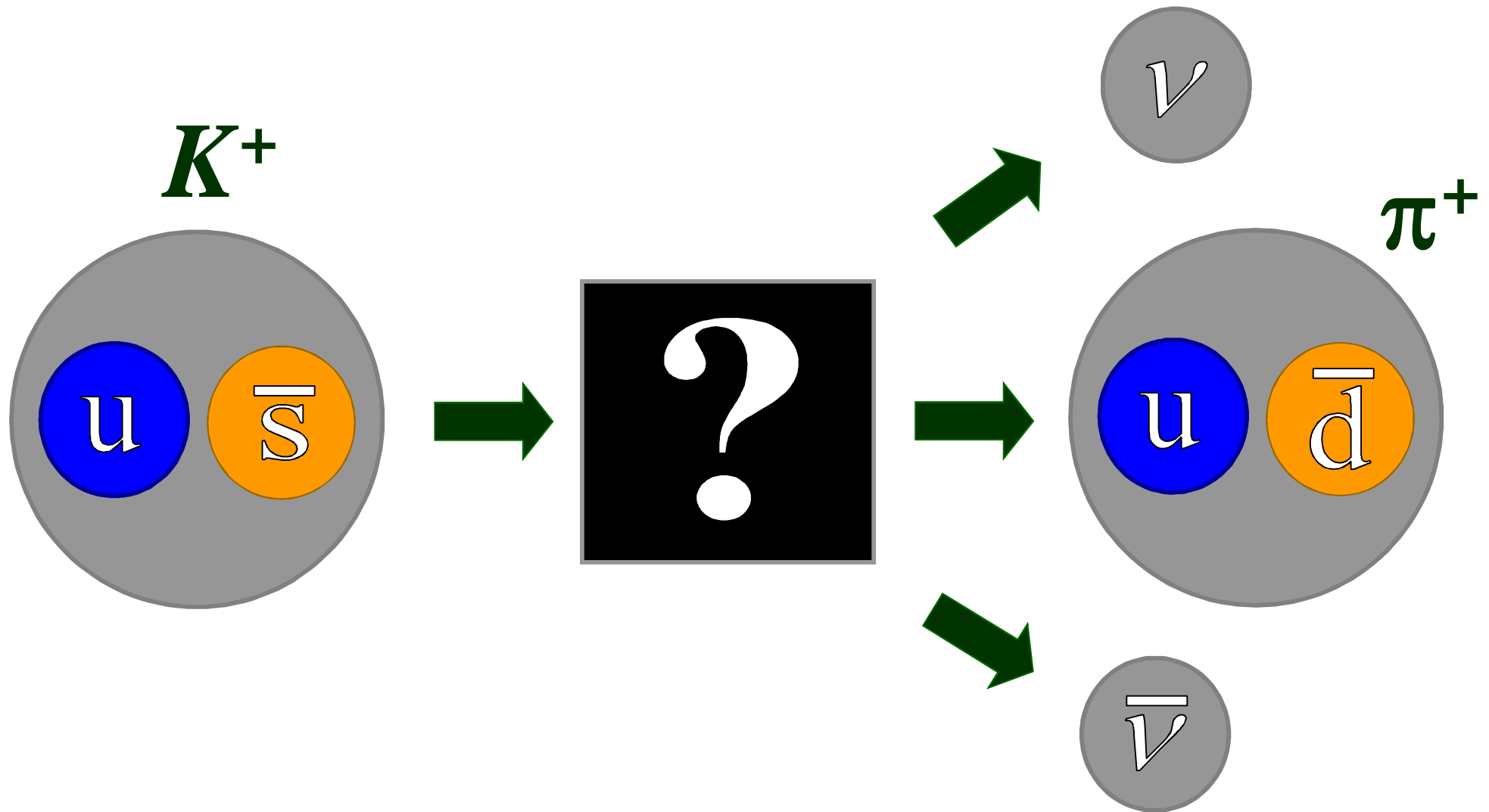
LHC

## Precision Frontier

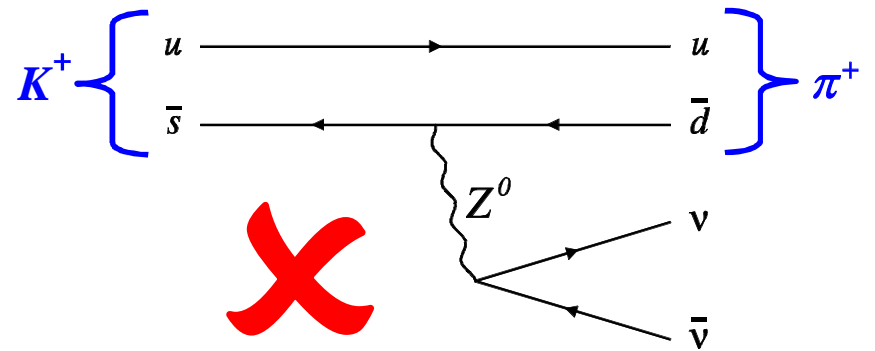
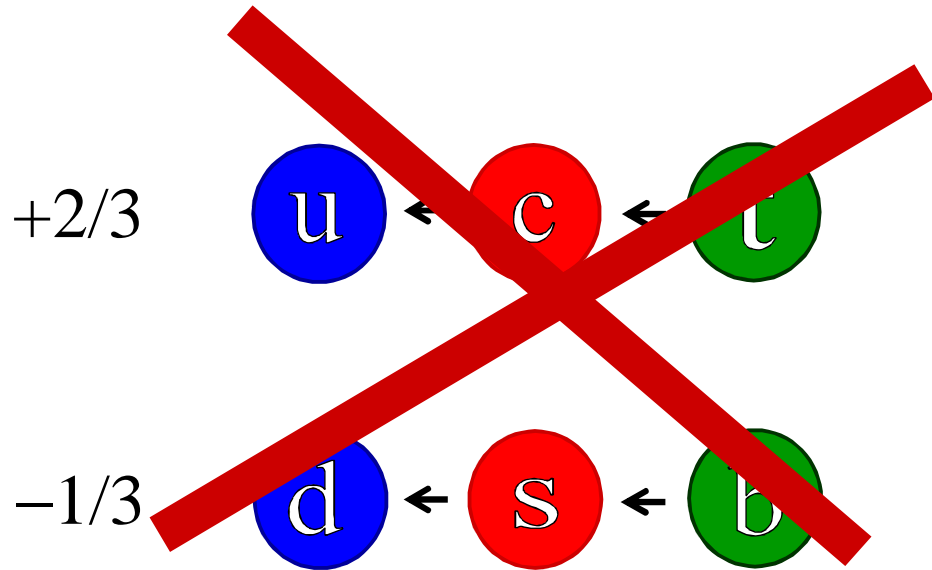


Rare decays such as  
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

To understand why  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  is rare, we need to look at the decay of s-bar to d-bar

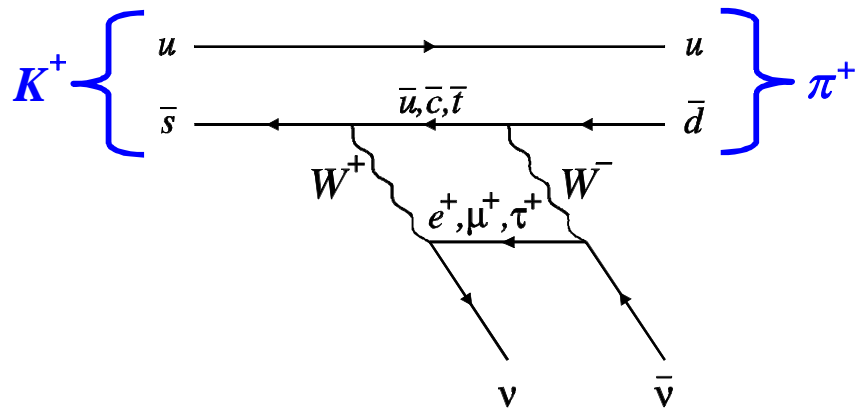


$K^+ \rightarrow \pi^+ \nu \bar{\nu}$  cannot proceed through a first-order weak process

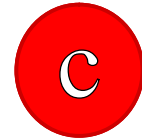




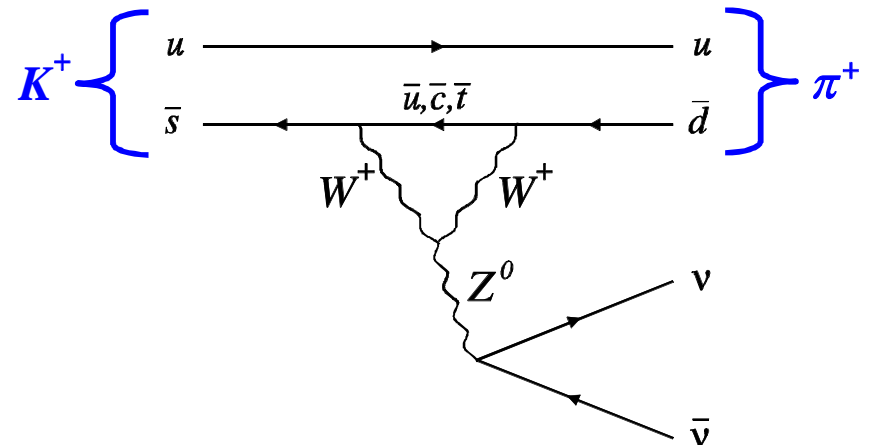
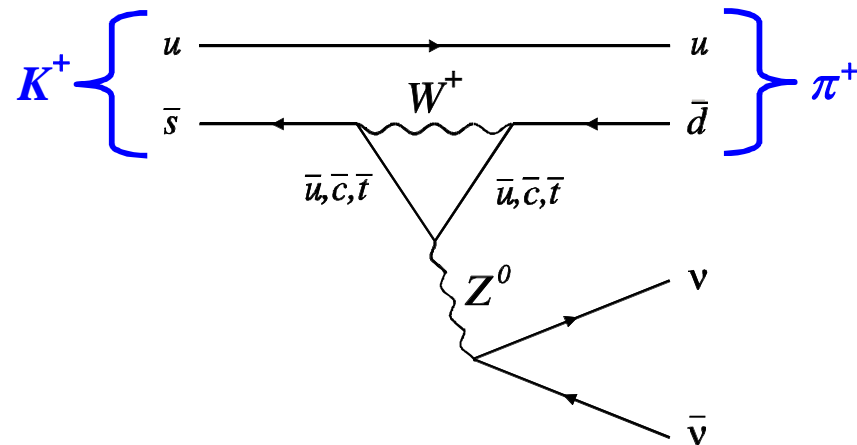
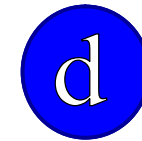
But  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  can proceed very slowly through second-order weak processes



+2/3



-1/3



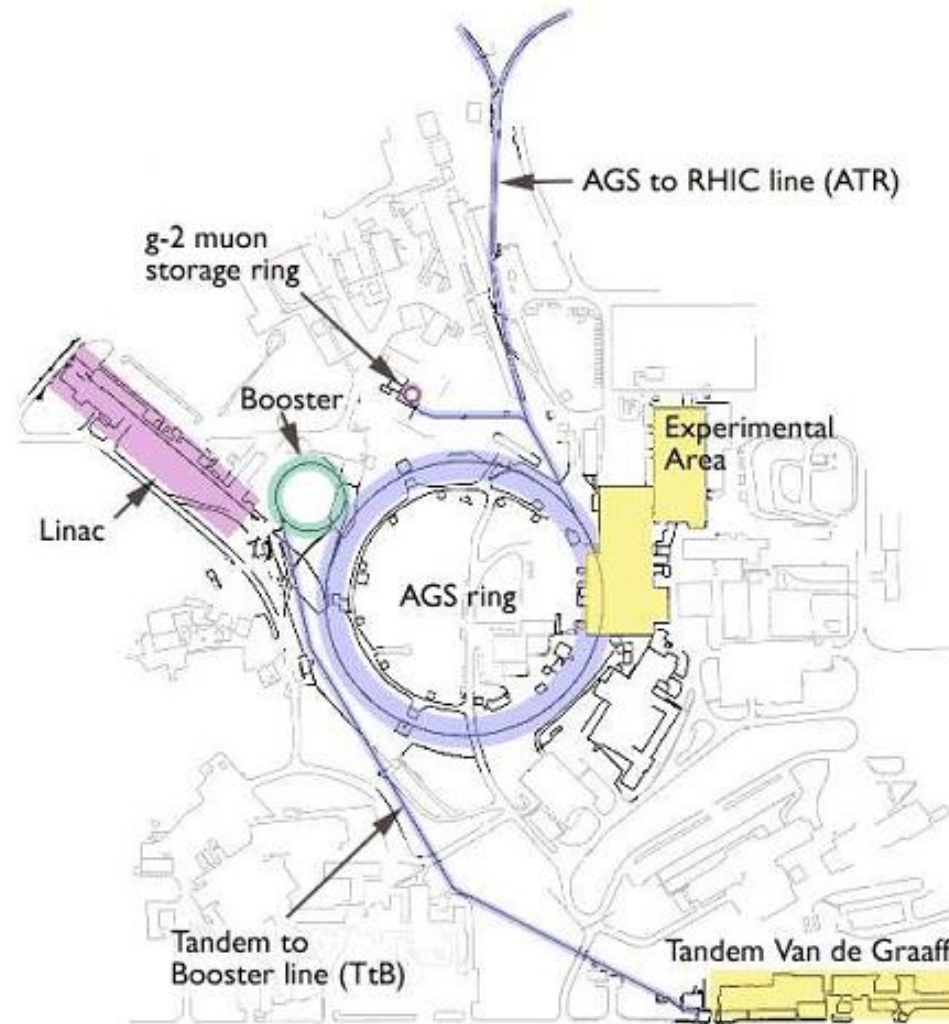
# Observing the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is an enormous experimental challenge

Standard Model branching  
ratio is  $(0.85 \pm 0.7) \times 10^{-10}$

1 in 12.5 billion!

Experimental signature is  
 $\pi^+ + \text{"nothing"}$

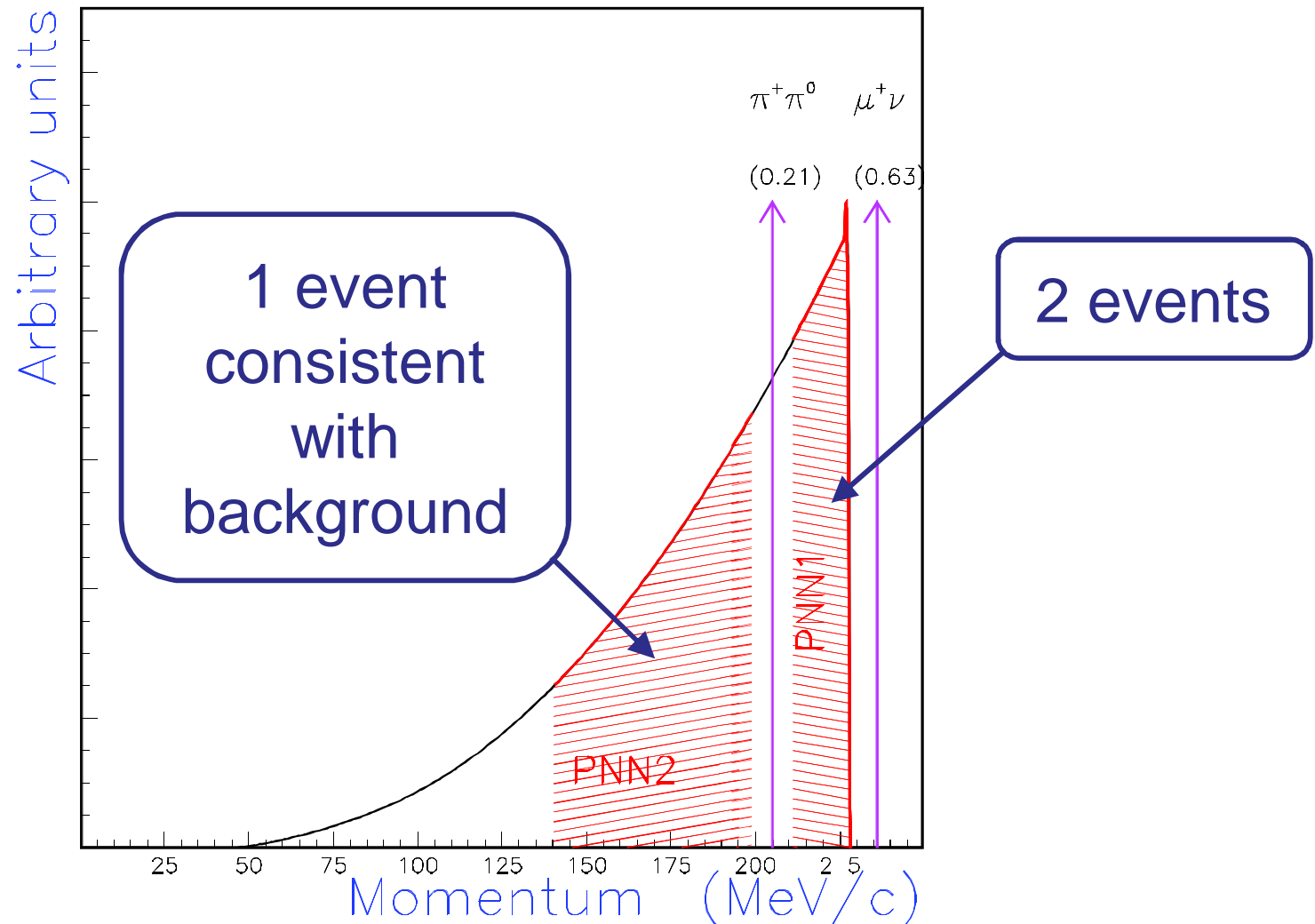
The first candidate events were observed by the E787 experiment at Brookhaven National Lab



The Alternating Gradient Synchrotron (AGS)

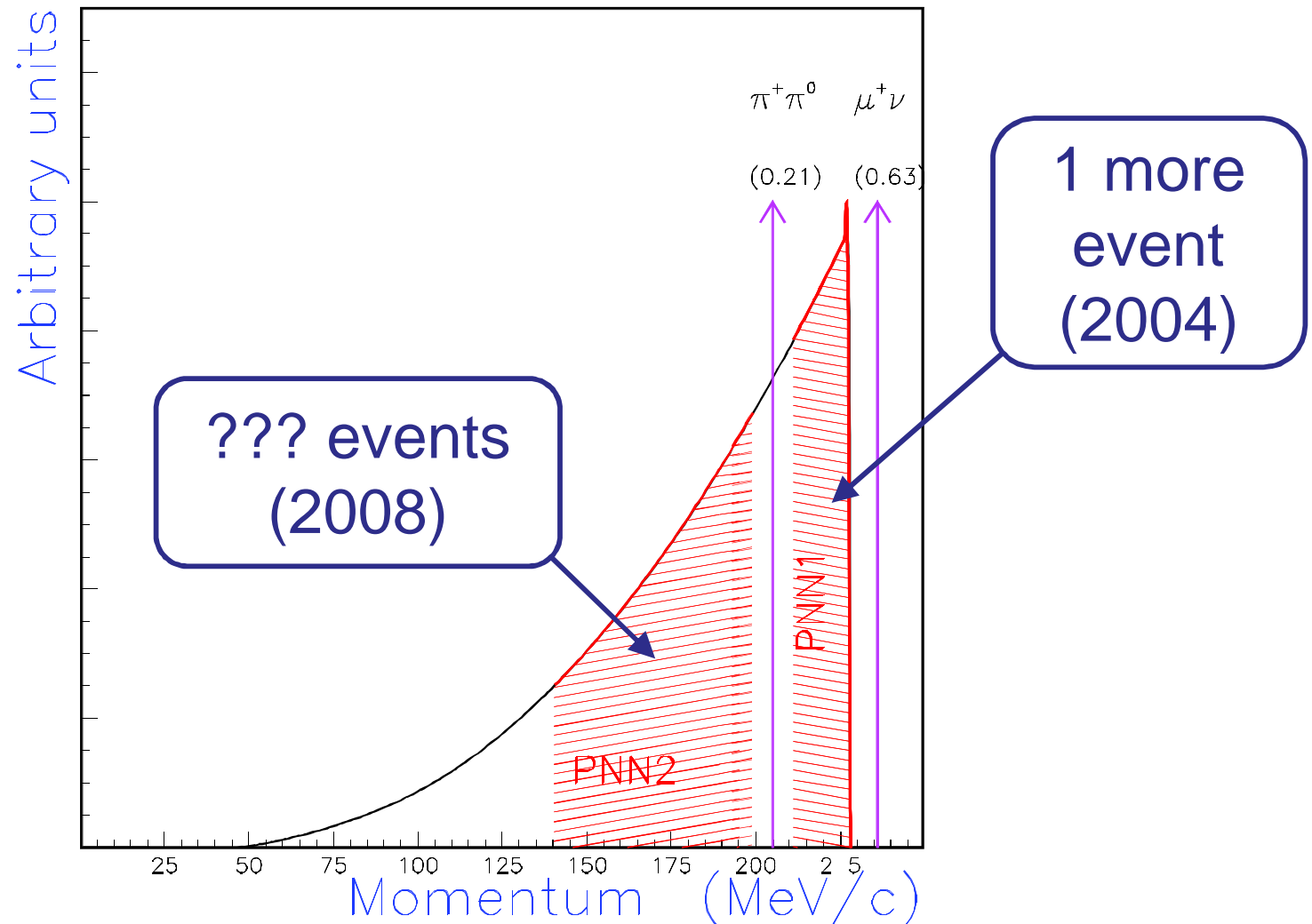


The  $K^+ \rightarrow \pi^+ \pi^0$  decay splits the momentum phase space in two, creating two regions of high signal-to-background

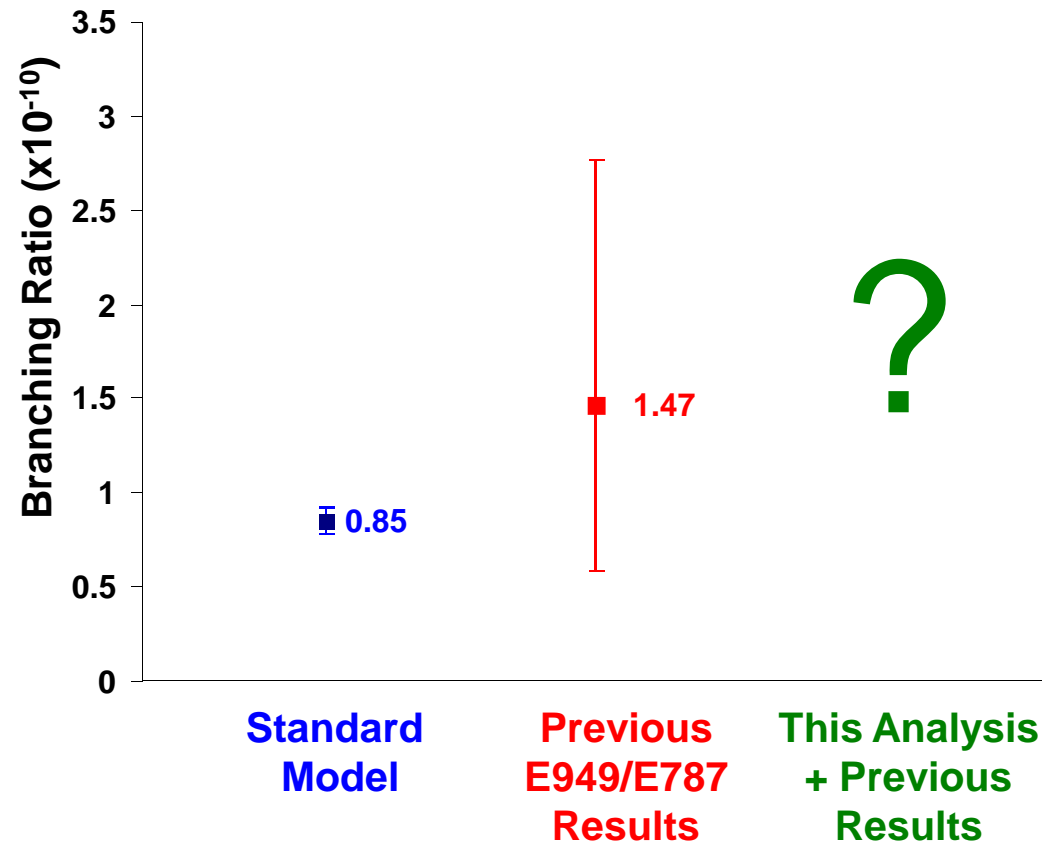


E787 = 1988-1998

The E949 experiment collected data in 2002 after major upgrades to the detector and beamline



BNL E949 & E787 have previously observed four candidate events showing that it can be done



A precision measurement of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$   
probes for new physics

The rest of the talk  
focuses on the PNN2  
region and how E949  
overcame the difficulty  
of observing

$$K^+ \rightarrow \pi^+ \nu \bar{\nu}$$

```
graph TD; A[Experimental Techniques] --> B[Analysis Techniques]; B --> C[Final results];
```

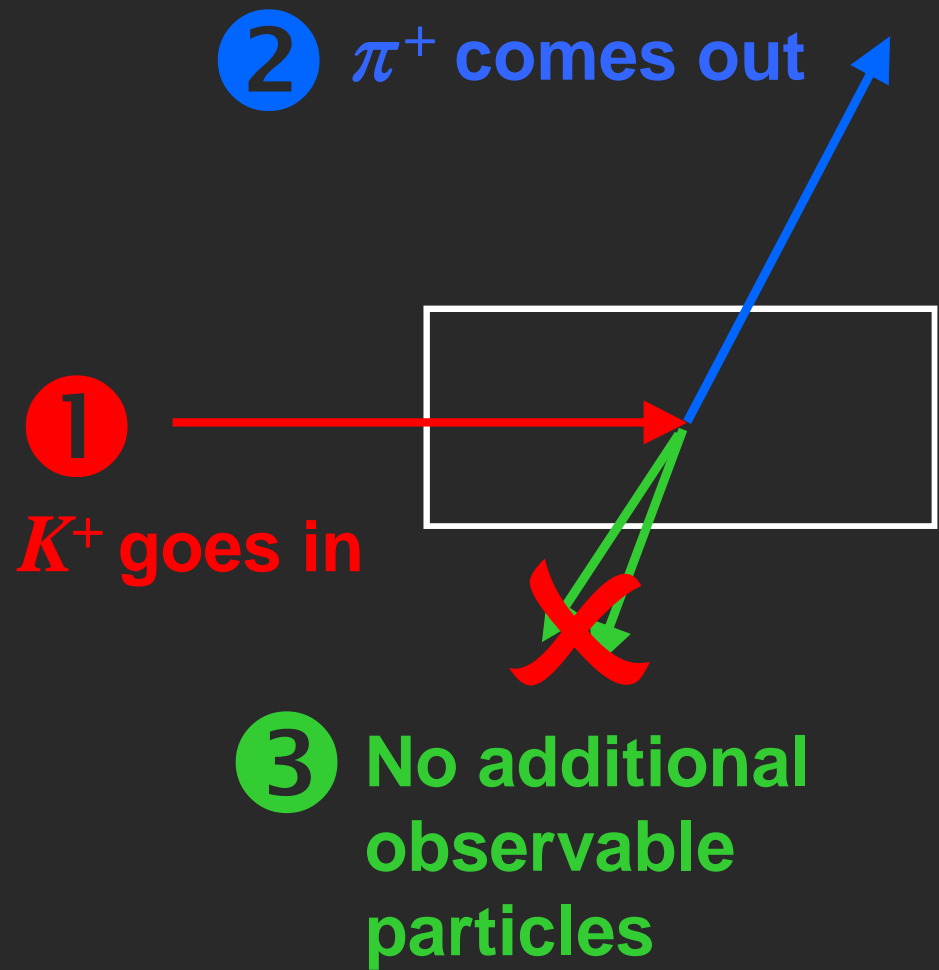
Experimental  
Techniques

Analysis  
Techniques

Final  
results

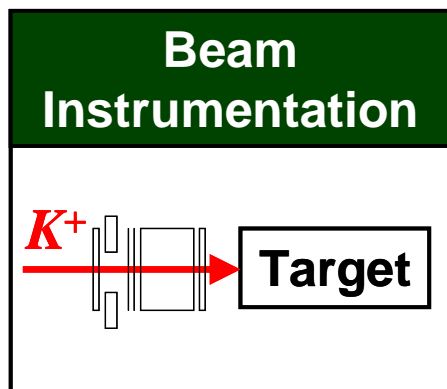
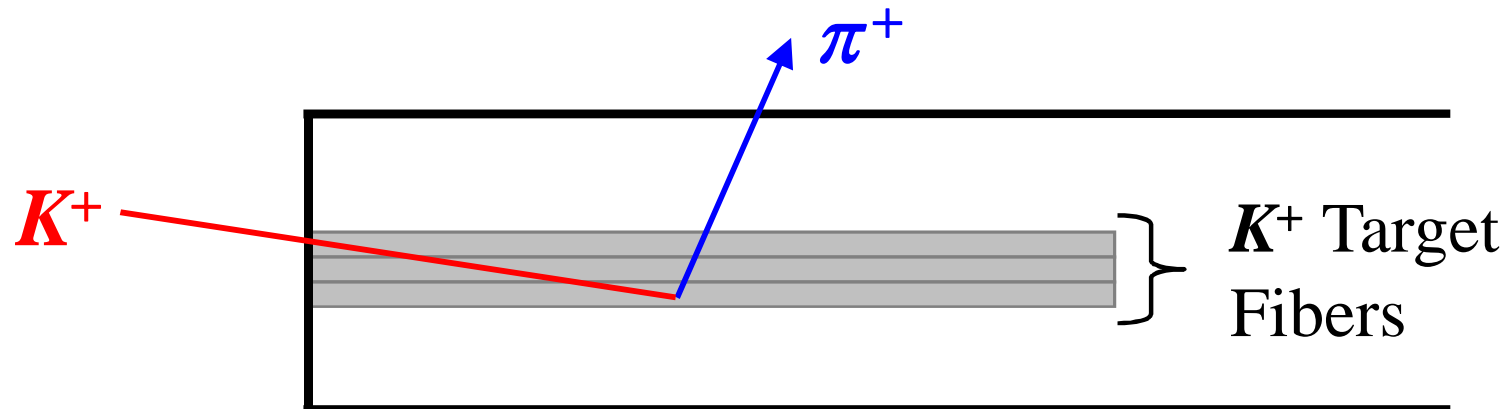


The experimental  
challenge is to observe  
 $\pi^+$  + "nothing"

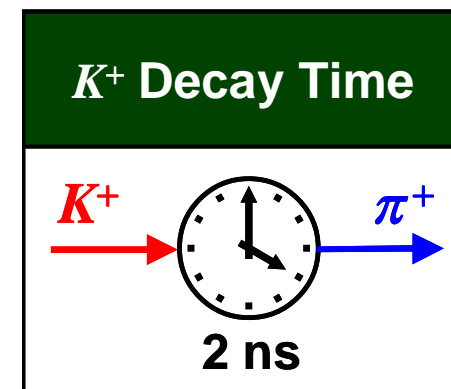


1

700 MeV/ $c$  kaon enters and decays-at-rest in the scintillator-fiber target



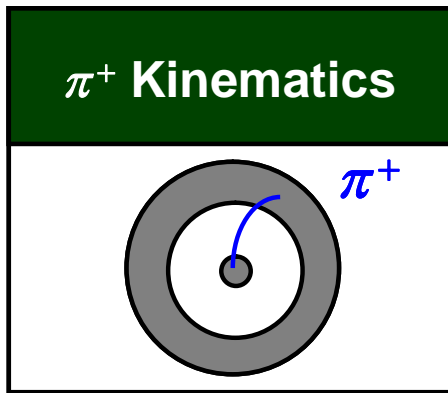
Beam instrumentation is used to identify a single  $K^+$  from the beam



Kaon comes to rest in the target and we wait at least 2 ns for  $K^+$  to decay

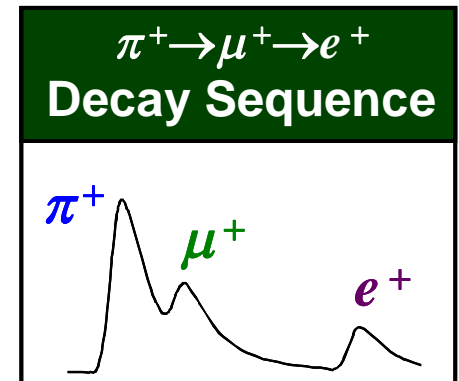
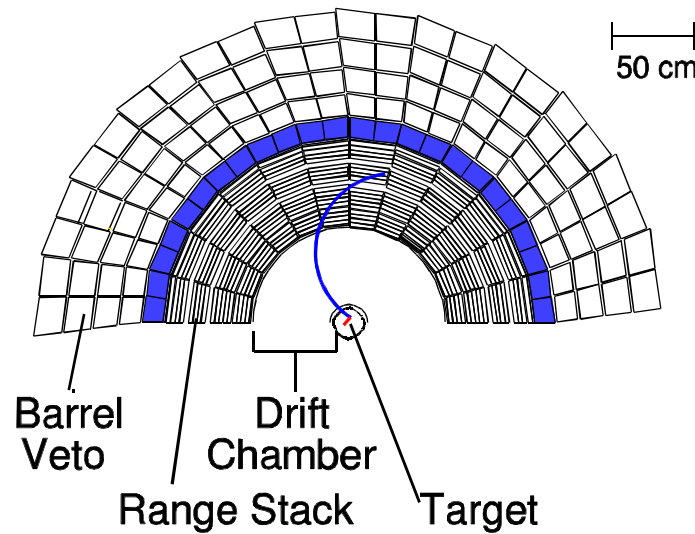
# 2

Pion comes to rest in the scintillator range-stack after traversing the drift chamber



$\pi^+$  momentum is measured in the drift chamber

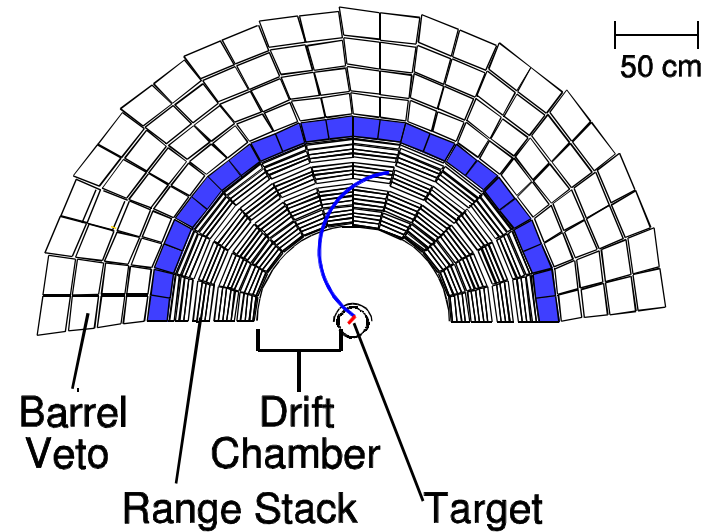
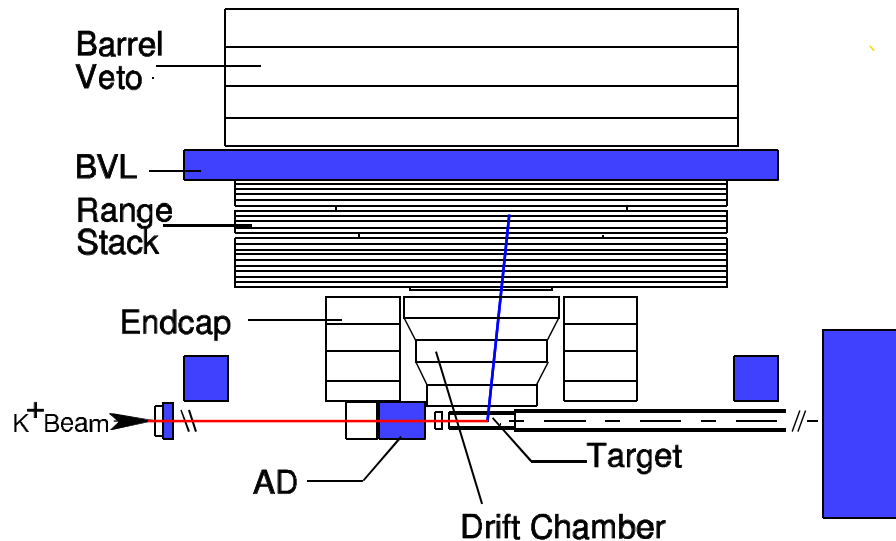
$\pi^+$  range and energy are measured target and range-stack



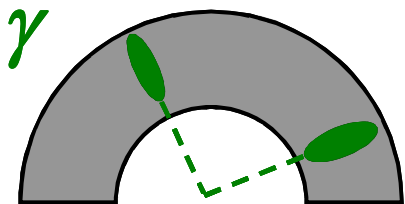
$\pi^+ \rightarrow \mu^+ \rightarrow e^+$  decay sequence is observed in the range-stack scintillator

# 3

## Veto additional charged particle and photon activity

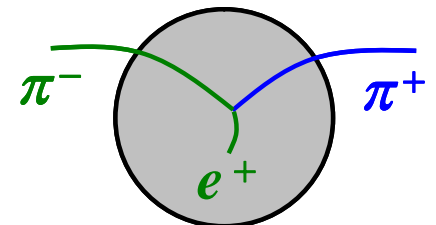


### 4 $\pi$ Photon Veto



Pattern recognition is used in the target, drift chamber and range-stack

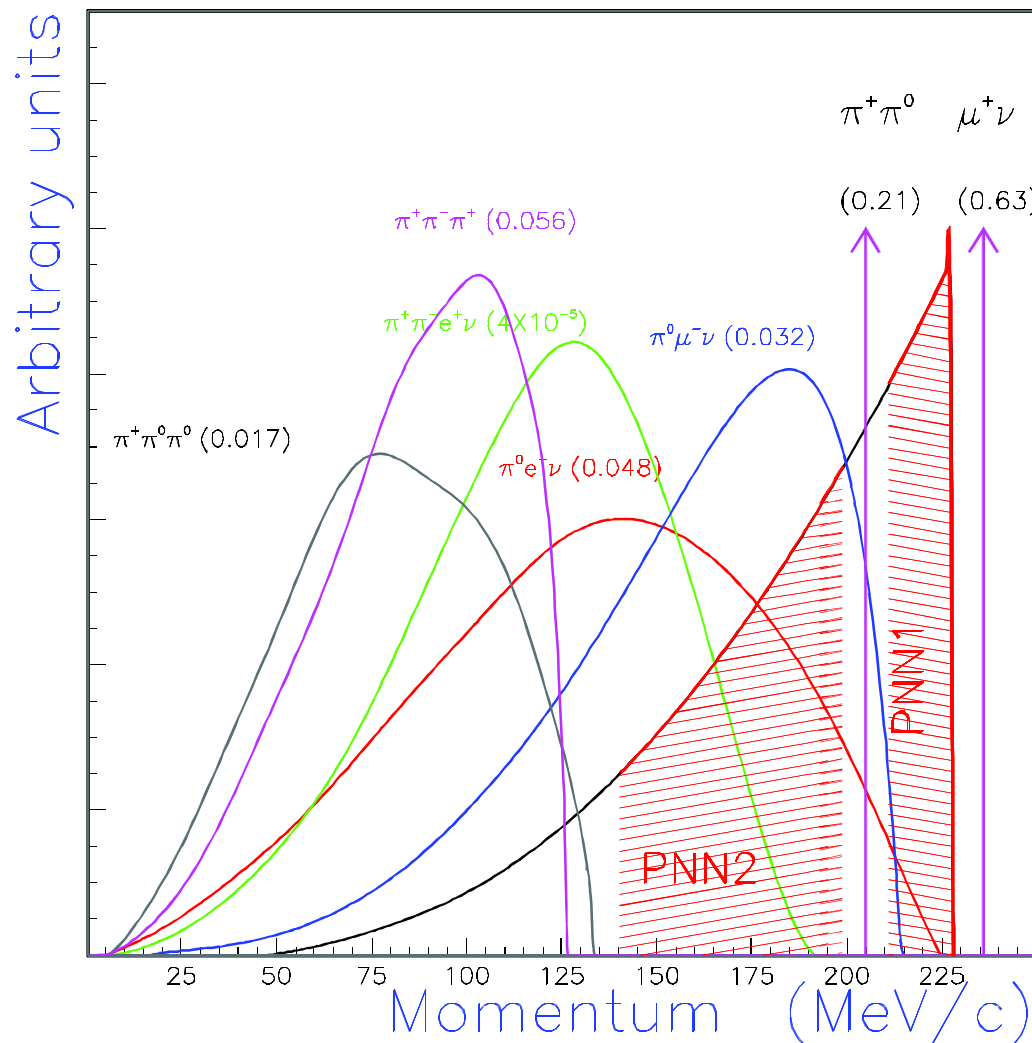
### Veto Additional Charged Tracks





To reduce potential bias,  
we use a “blind” analysis technique

In our blind analysis, backgrounds that can mimic  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  are identified *a priori*



Our blind analysis technique is based on eliminating everything that is not  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  without directly examining our signal region

Take all events in the PNN2 high  
signal-to-background region

=

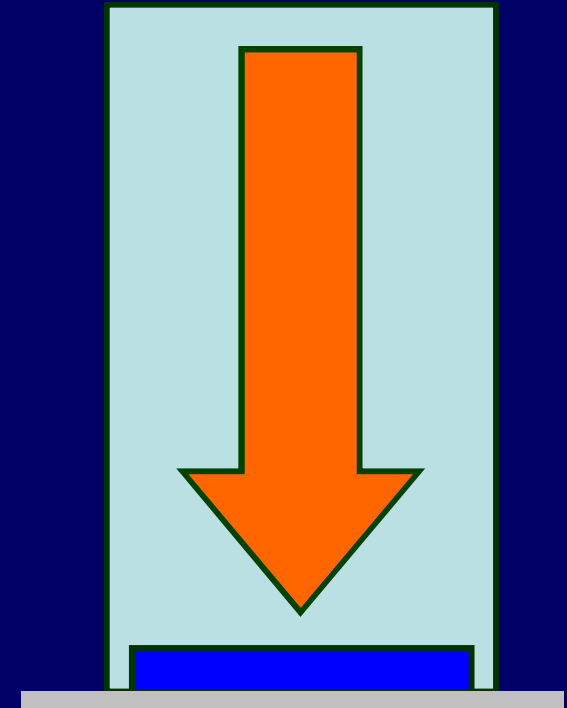
Events identified as being  
NOT  $K^+ \rightarrow \pi^+ \nu \nu$

=

Candidate  
 $K^+ \rightarrow \pi^+ \nu \nu$  events

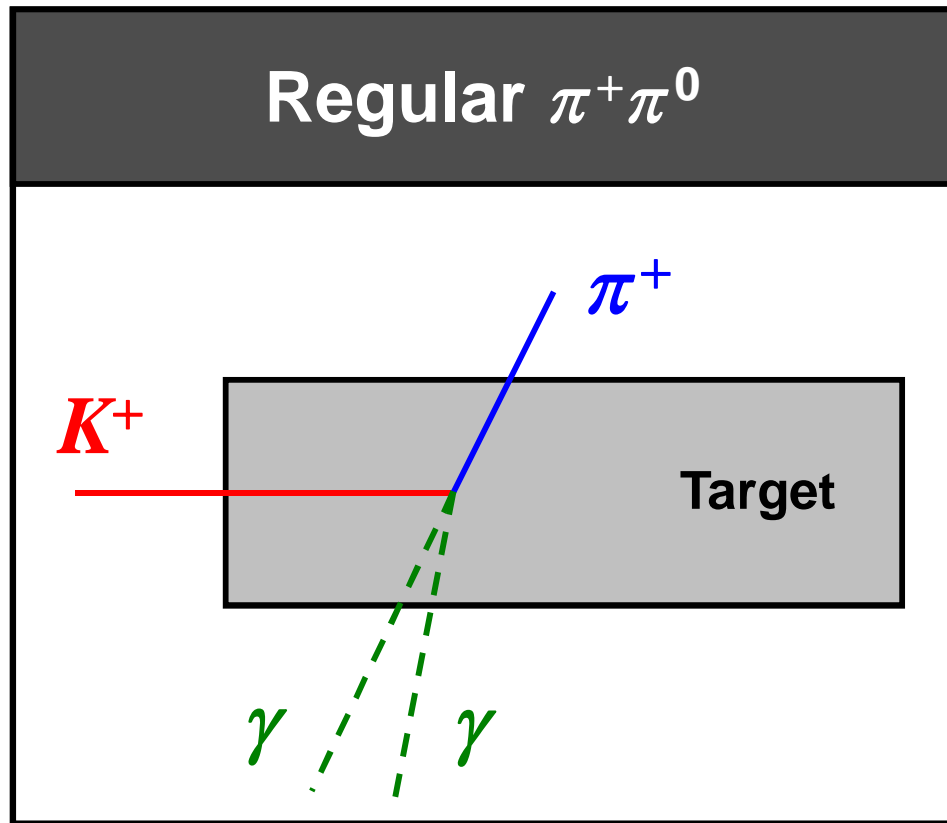
The key is VERY large  
suppression of  
background

**Total  
Background**

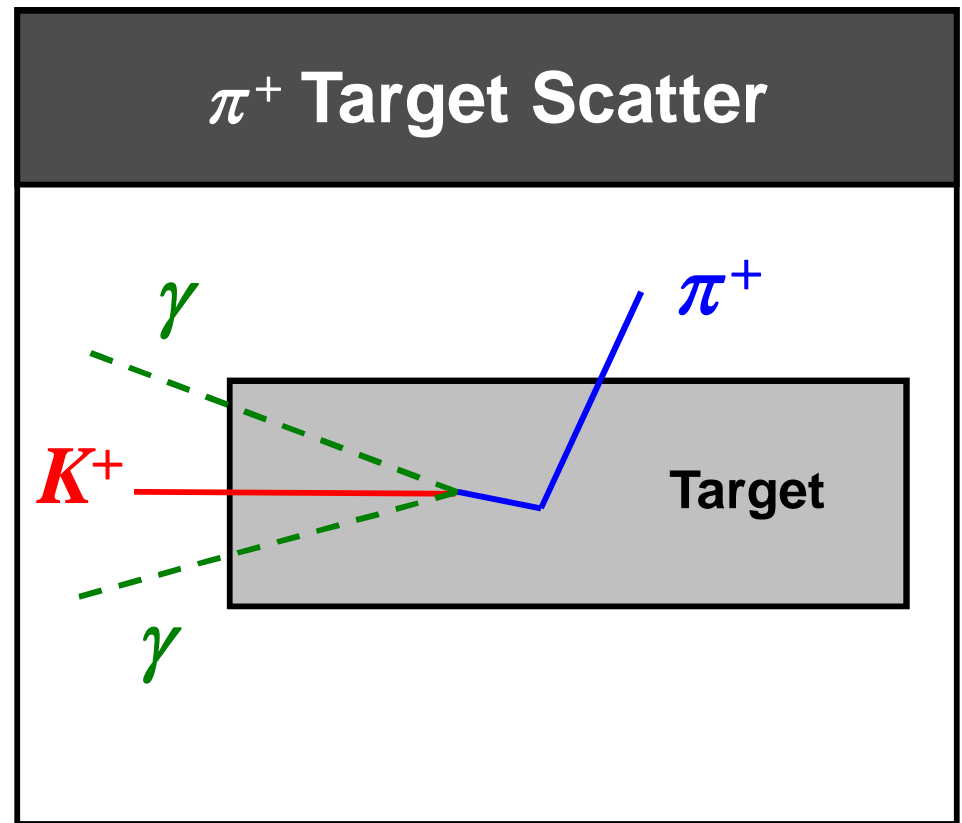




The most troublesome background is  $\pi^+\pi^0$  when the  $\pi^+$  scatters in the target

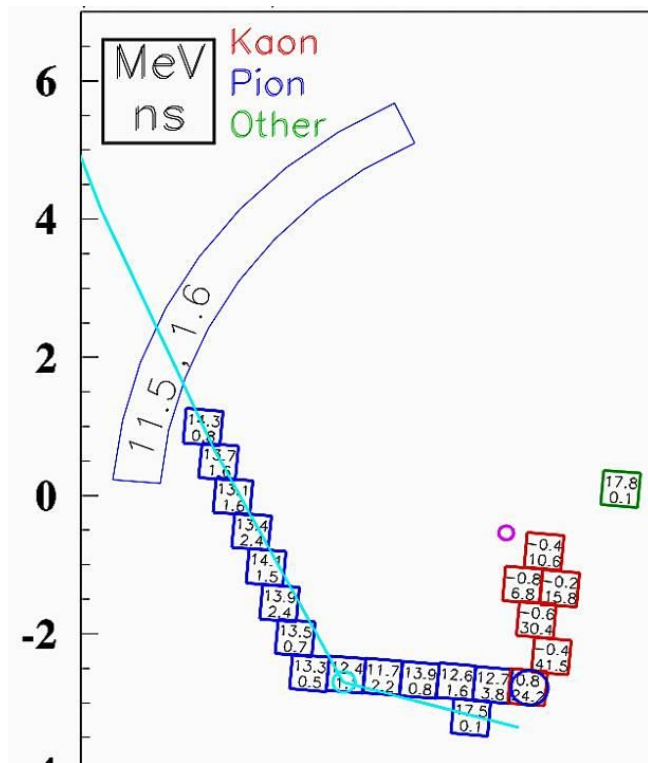


$\pi^+$  and  $\pi^0$  are back to back so photons are directed to efficient part of the photon veto

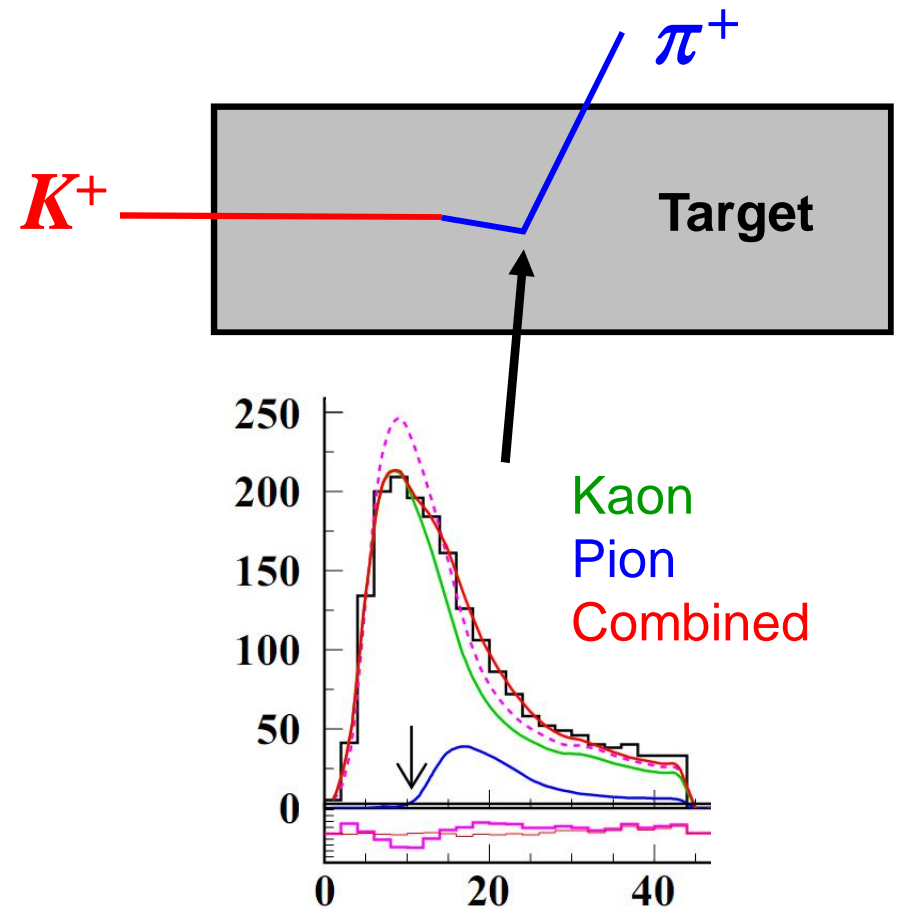


When the  $\pi^+$  scatters in the target it loses energy and the photons lose directional correlation with the  $\pi^+$

# This background is suppressed by the photon veto and identification of $\pi^+$ scattering

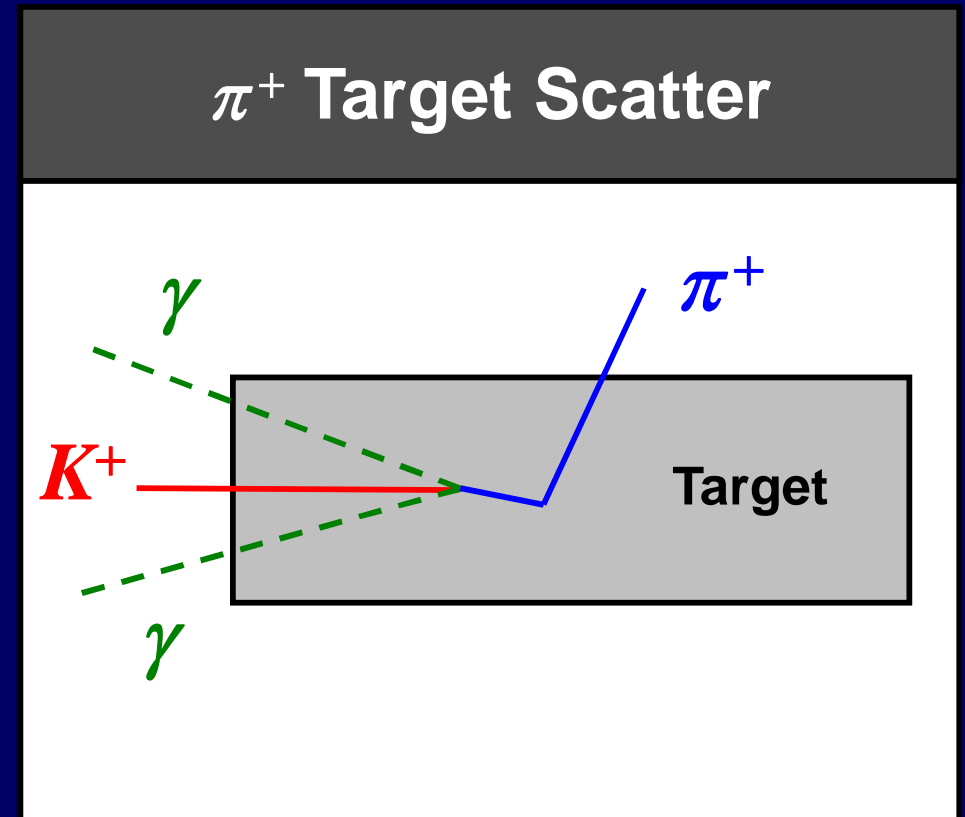


A scatter can be identified by finding a kink in the  $\pi^+$  track



A scatter can also be identified by large energy deposits in a pion fiber or hidden energy in a kaon fiber

The  $\pi^+$  target-scatter background will be used to illustrate the bifurcation background estimation technique



# The photon veto and the target-scatter ID cuts are used to define the bifurcation phase space

The signal region **A** cannot be examined directly.

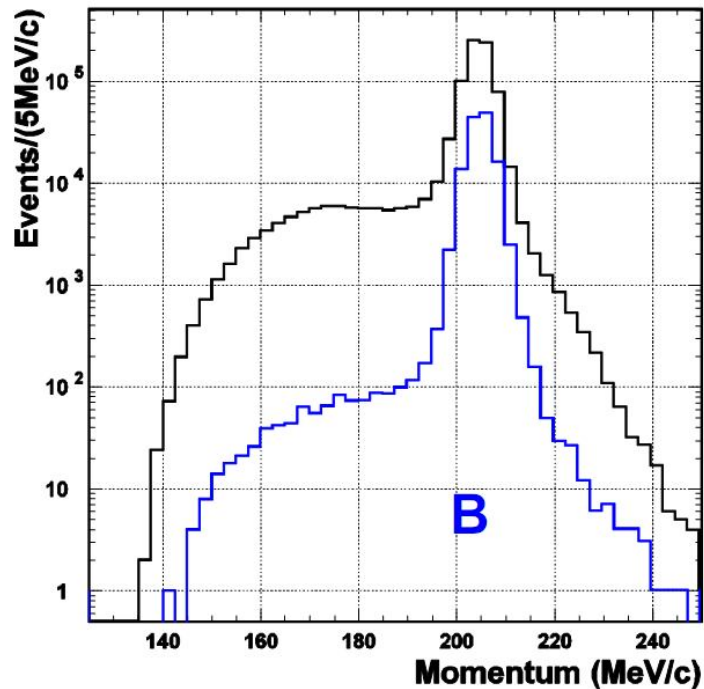
For uncorrelated cuts:

$$\mathbf{A/B} = \mathbf{C/D}$$

		P	F		
Photon Veto	B		D	F	
	A		C	P	
		Target-scatter ID			



Photon veto is inverted (black curve) and the target cuts are applied (blue curve)



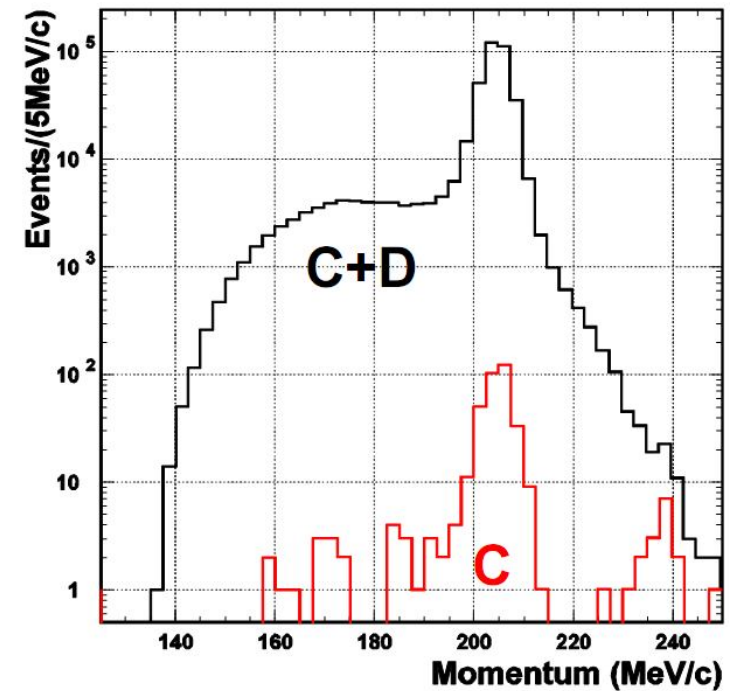
Photon Veto	B	D
	A	C
Target-scatter ID		

Measure B

Target-scatter cuts are inverted (black curve)  
and the photon veto is applied (red curve)

Measure  
C+D and C

Photon Veto	Target-scatter ID	
	B	D
A		
		C



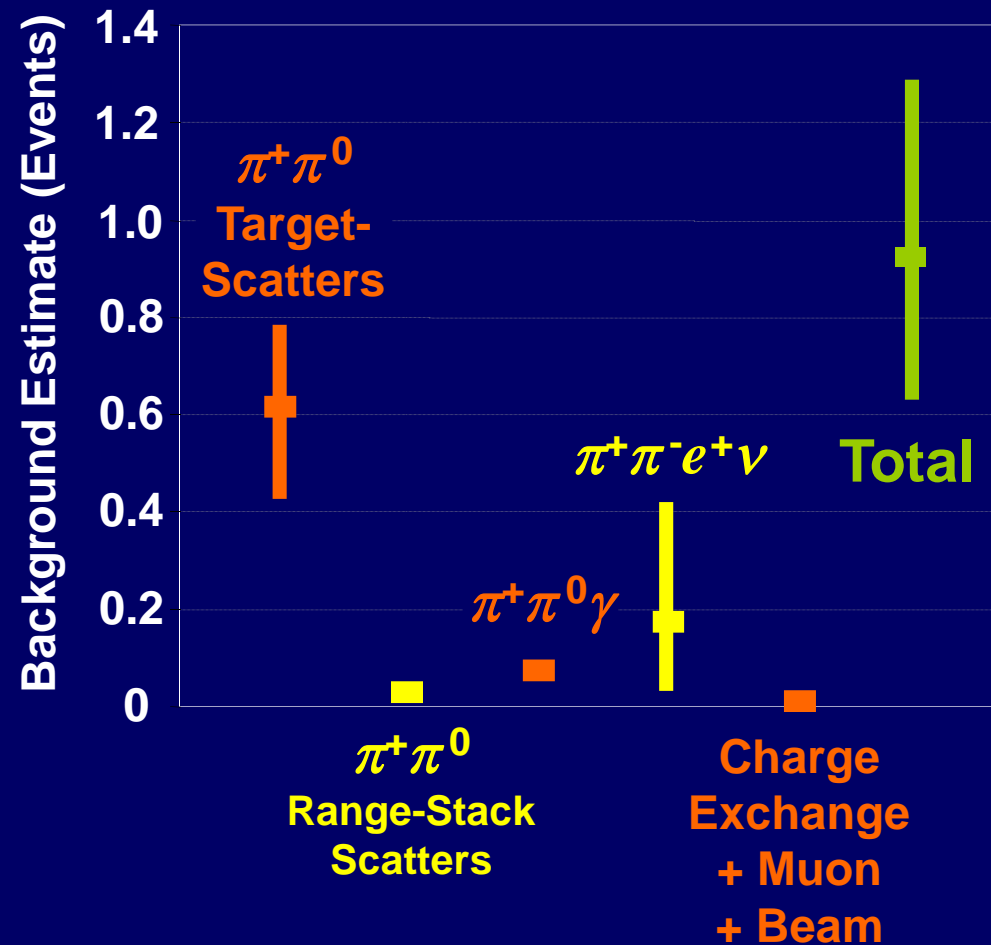
The number of  $\pi^+$  target-scatter events is estimated using the number of events in each of the other regions

Background  
estimate:  
**A** = BC/D

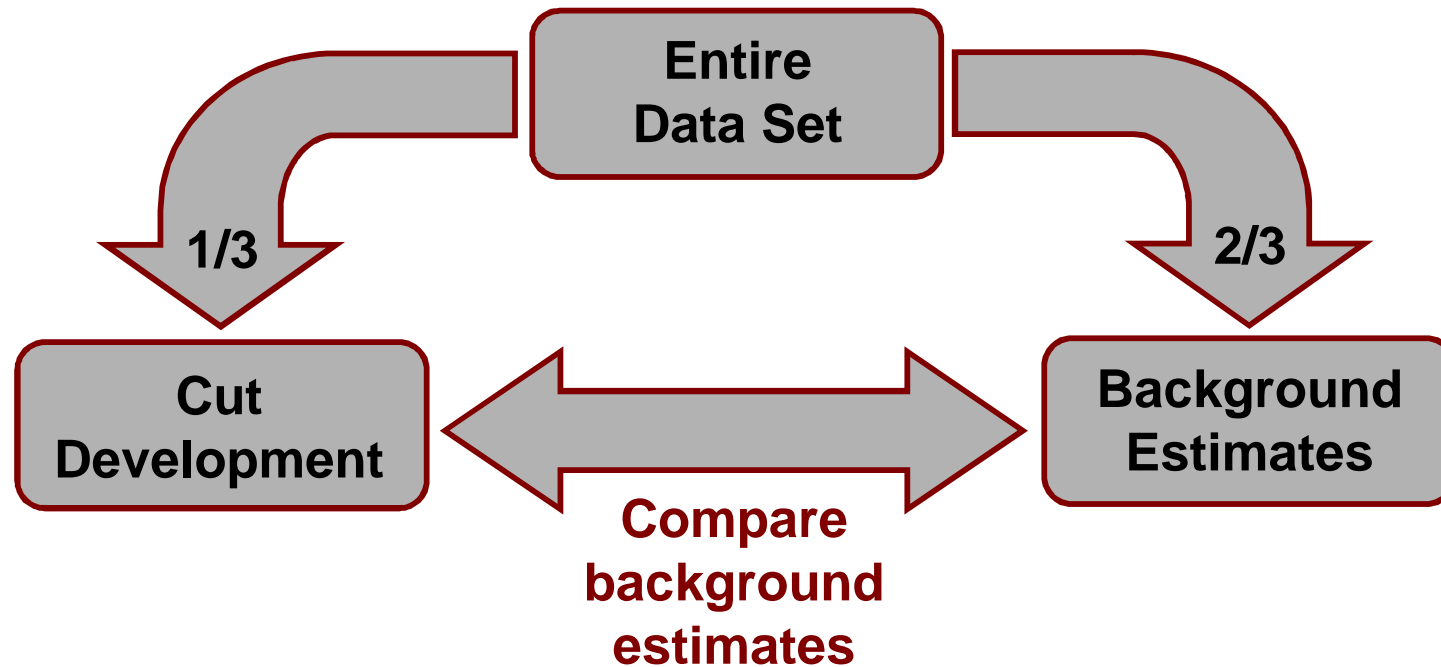
Photon Veto	B	D
	A	C
Target-scatter ID		

Result:  
 $0.619 \pm 0.150$   $^{+0.067}_{-0.100}$

The total background  
was suppressed to  
below a single event  
from  $1.70 \times 10^{12}$   
kaon decays  
with a total acceptance  
of  $1.37 \times 10^{-3}$



Background estimates are performed using data different from those used to develop cuts



# Validation studies were performed...

To look for correlations between  
sets of bifurcation cuts

To search for additional  
background sources

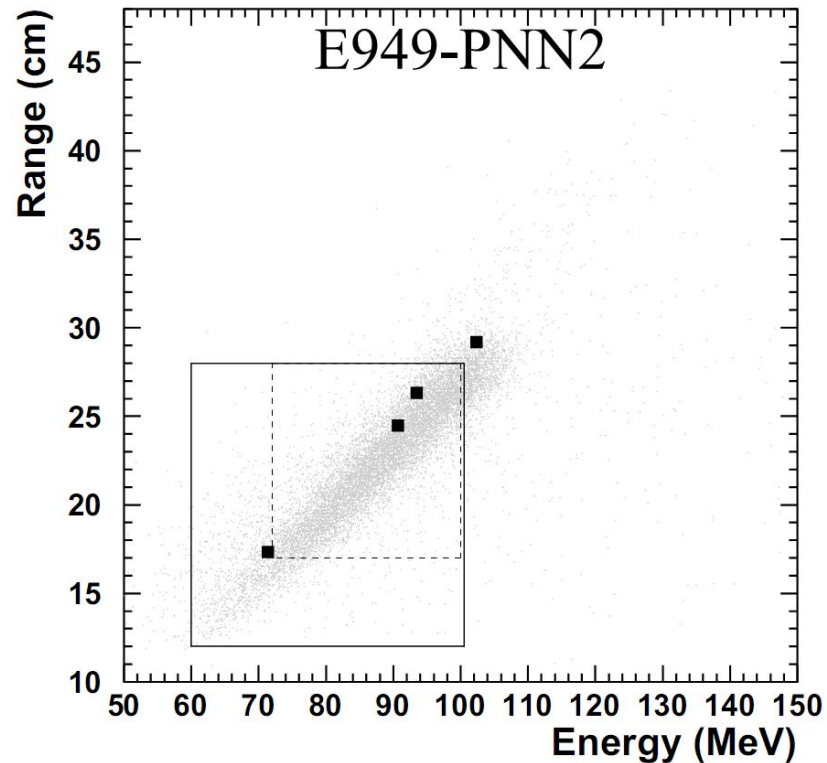
The signal region is  
only examined once all  
background estimates  
have been finalized.

It's time to  
open the box...



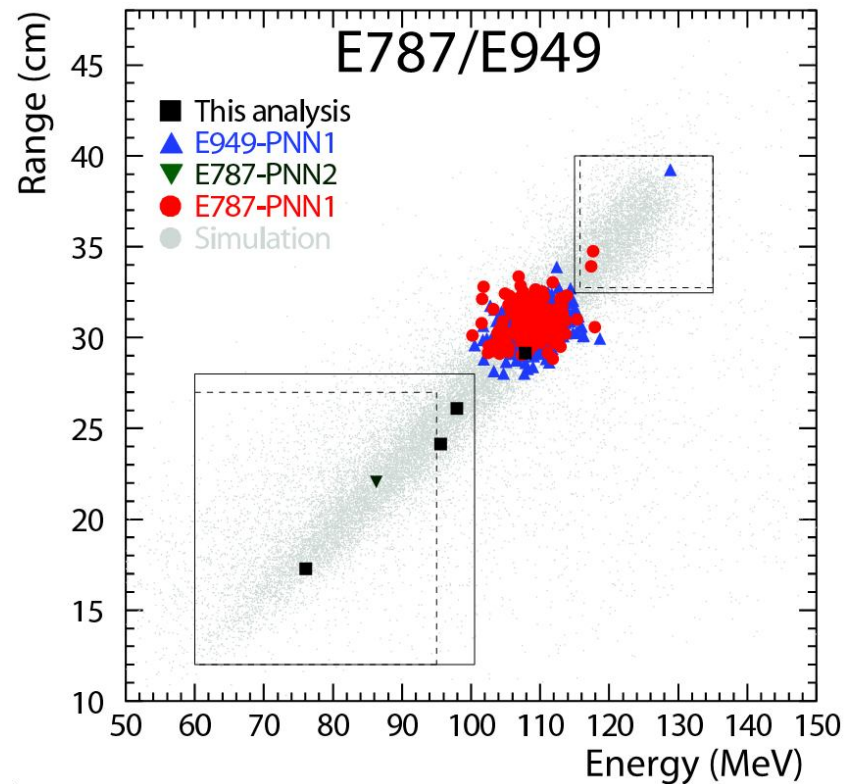


...and three new events were observed



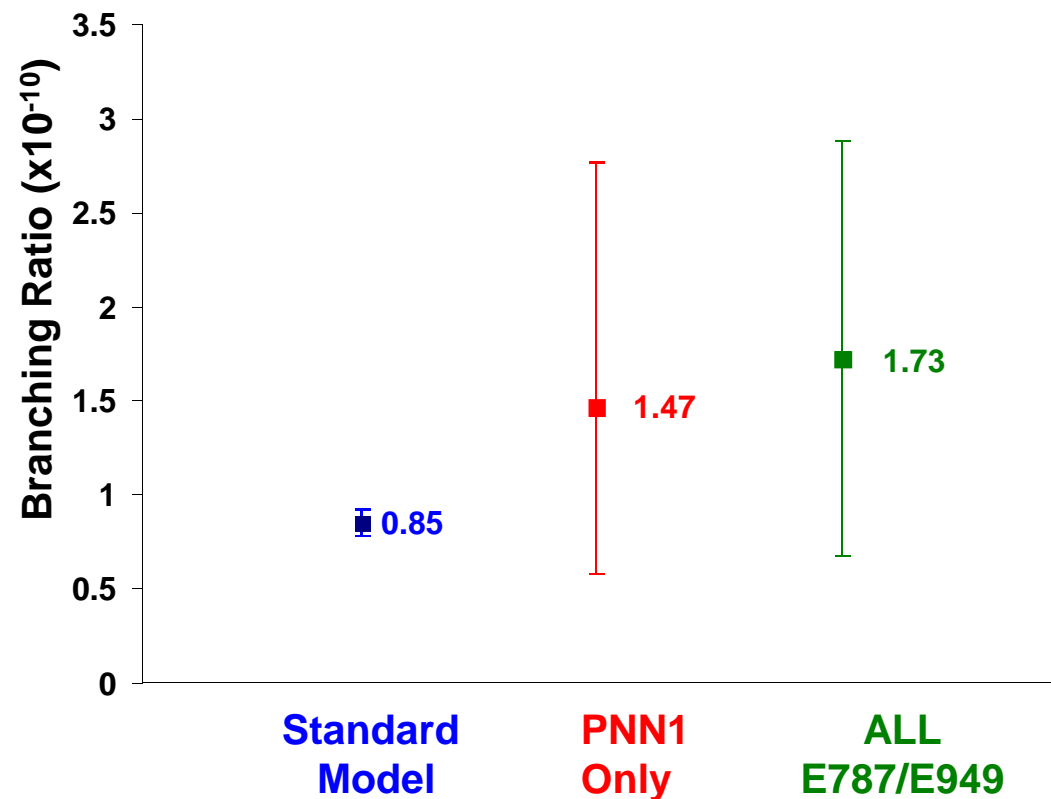
The probability that all three events were due to background only is 3.7%

# The E787/E949 experiment has observed 7 candidate events in total



The probability that all seven events were due to background only is 0.1%

The combined E787/E949 branching ratio remains consistent with the Standard Model expectation



# The next measurements of $K \rightarrow \pi \nu \bar{\nu}$ are just around the corner

KEK-E391a measured<sup>1</sup>  
 $\text{BR}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 6.7 \times 10^{-8}$

Detector moving to J-PARC  
as E14 with goal of  
observation of an event

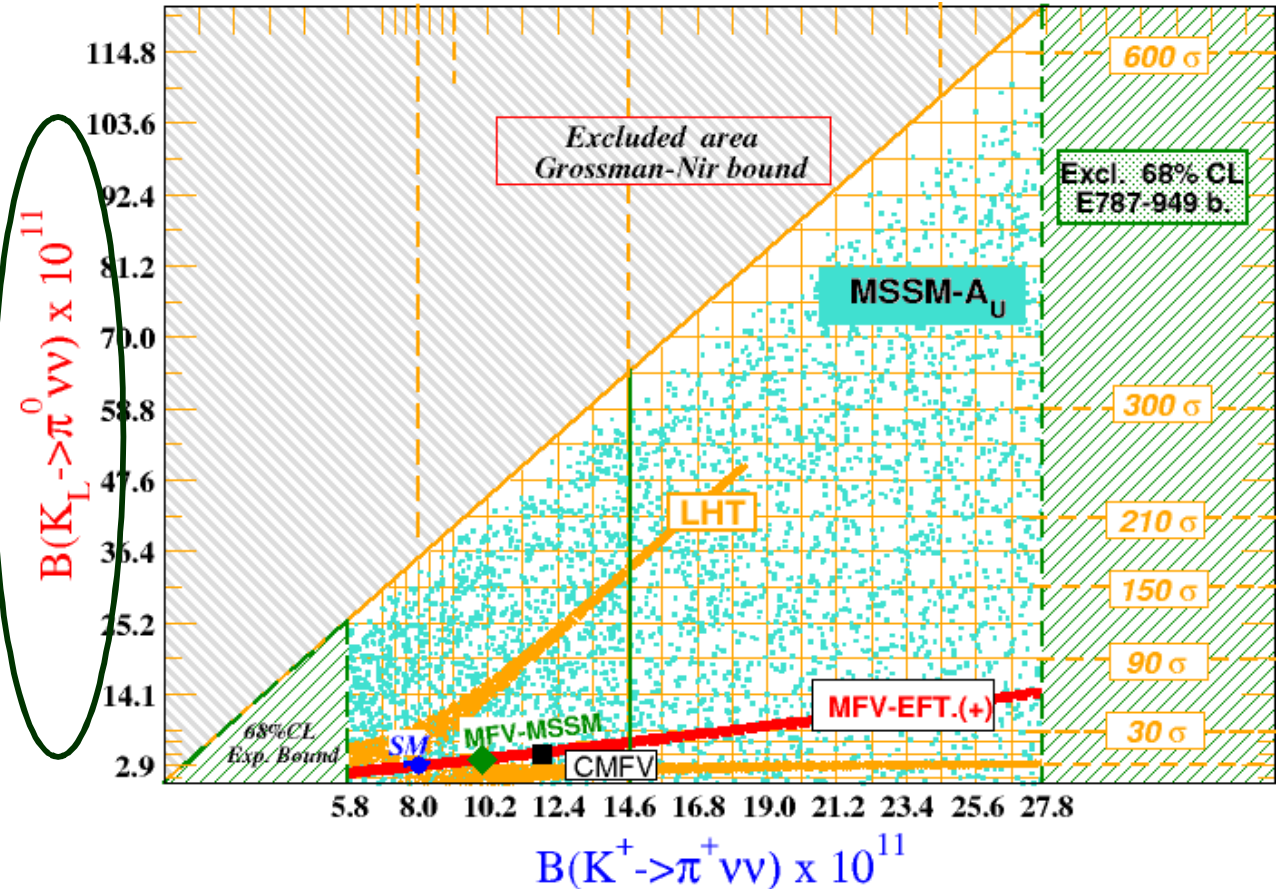


Figure: FlaviaNet - <http://www.lnf.infn.it/wg/vus/>

<sup>1</sup>E391a Collaboration, J. Ahn, et al., Phys. Rev. Lett. **100** (2008) 201802.

# The next measurements of $K \rightarrow \pi \nu \bar{\nu}$ are just around the corner

NA62 (formerly NA48/3)  
in preparation at CERN

<sup>2</sup>Goal is to measure 100  
events with S/B = 10:1

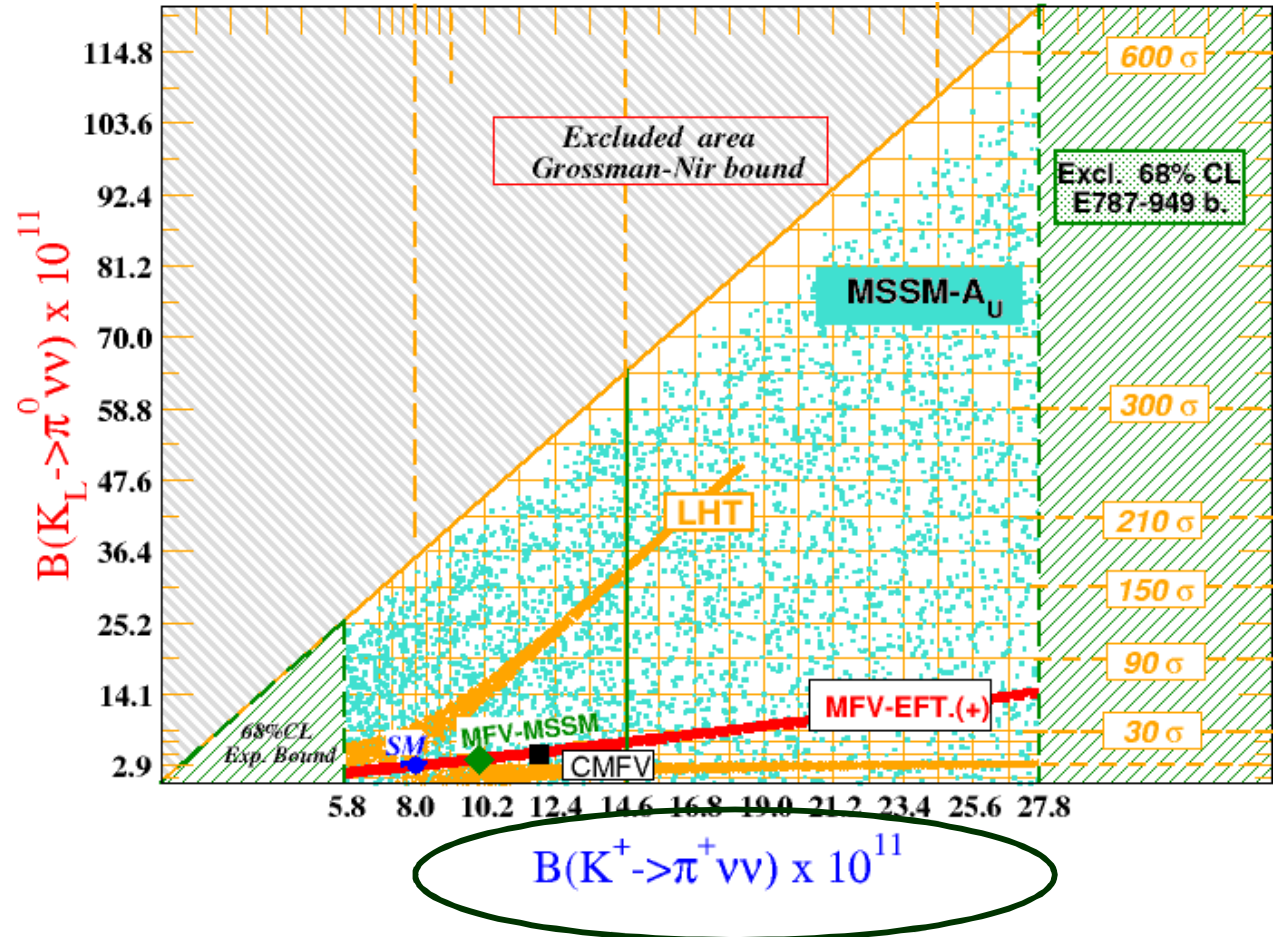
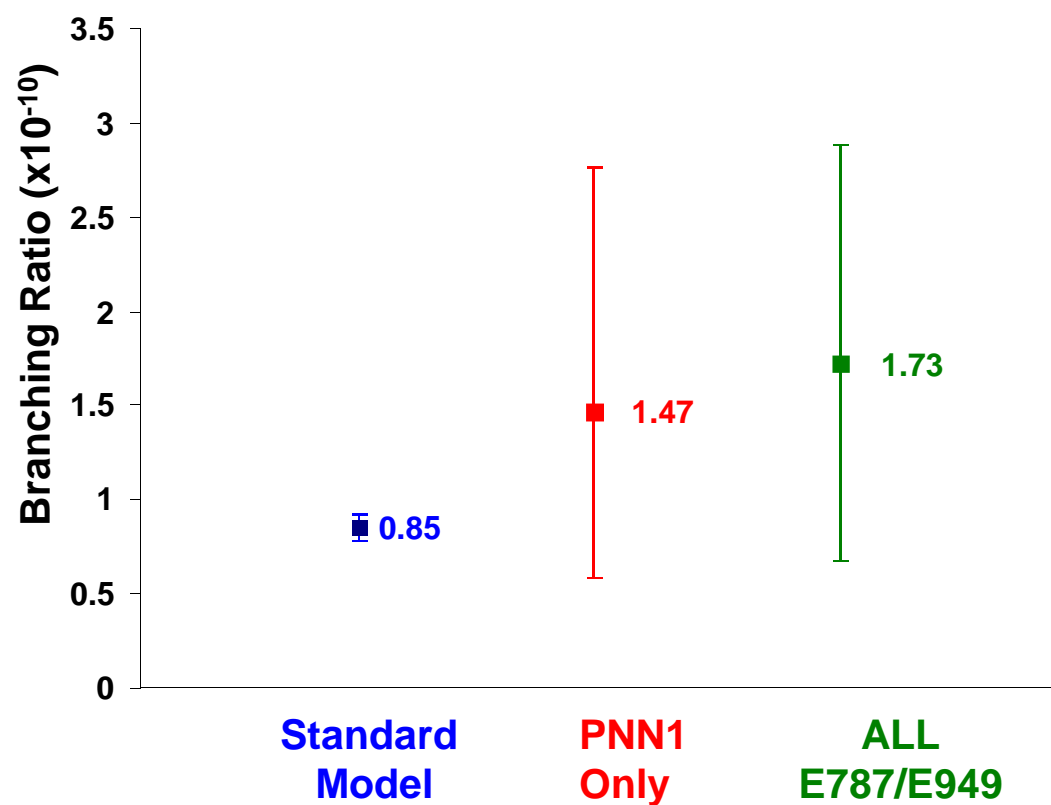
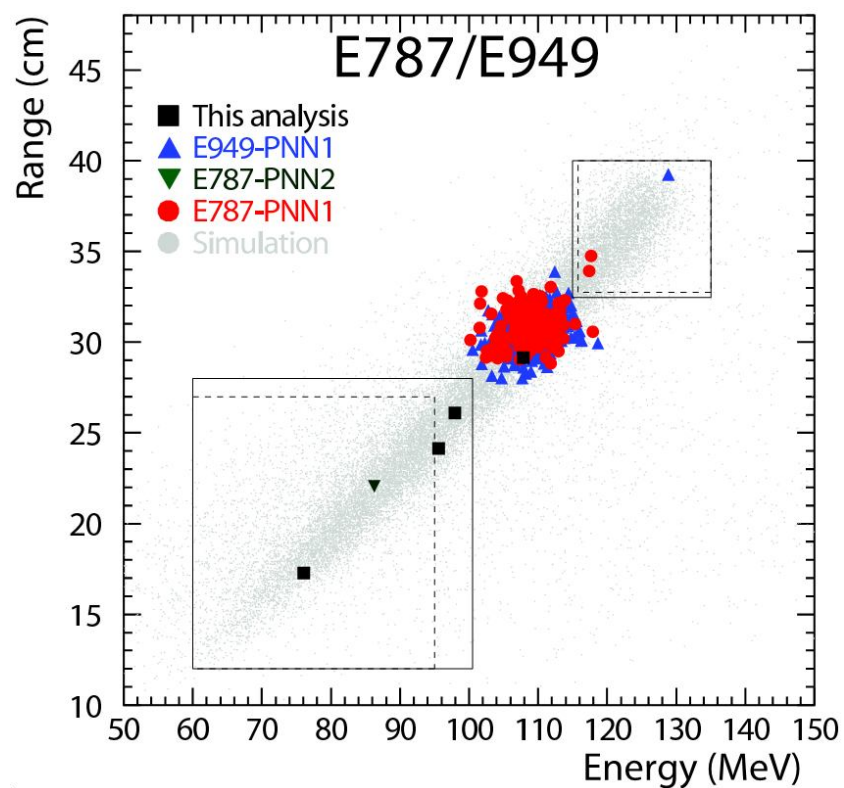


Figure: FlaviaNet - <http://www.lnf.infn.it/wg/vus/>

<sup>2</sup>G. Anelli et al., CERN-SPSC-2005-013, CERN-SPSC-P-326, Jun 2005.

# Thank you

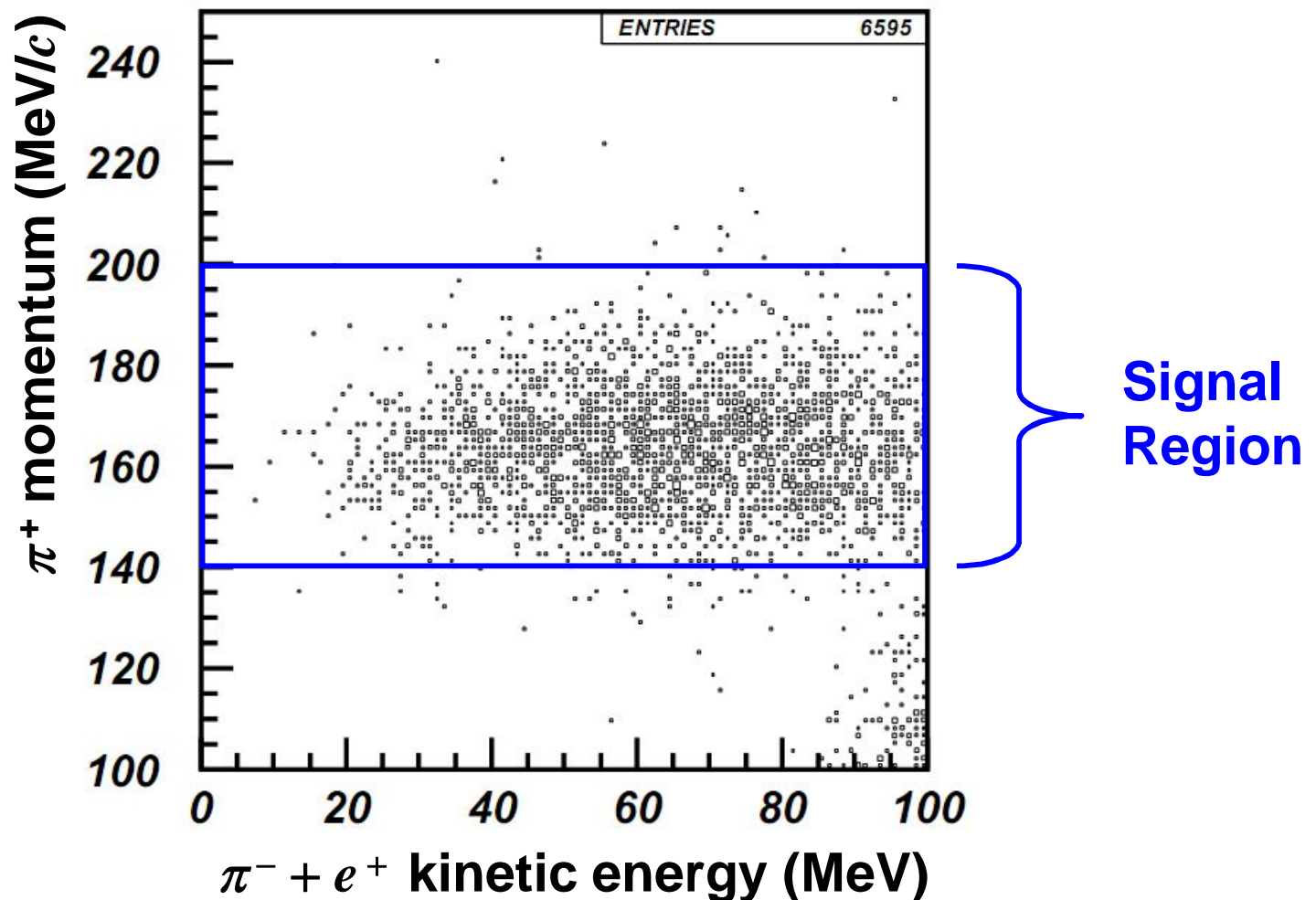


**END**



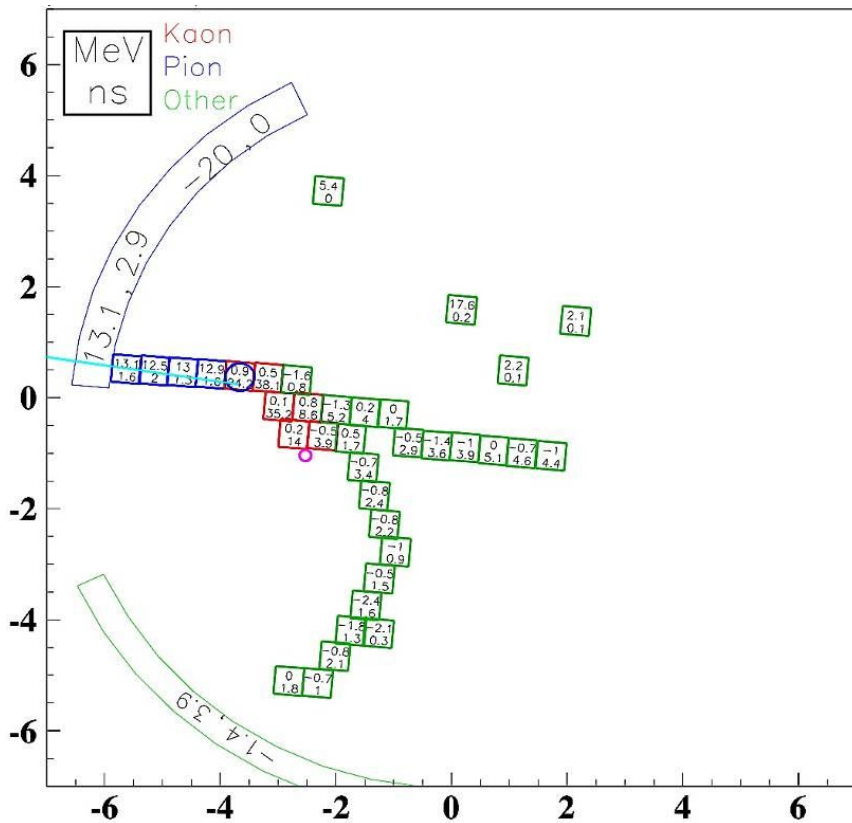
The  $\pi^+\pi^-\nu$  decay can mimic signal when the  $\pi^-$  and  $e^+$  have low kinetic energies

**Simulated  $K^+ \rightarrow \pi^+ \pi^- e^+ \nu$**

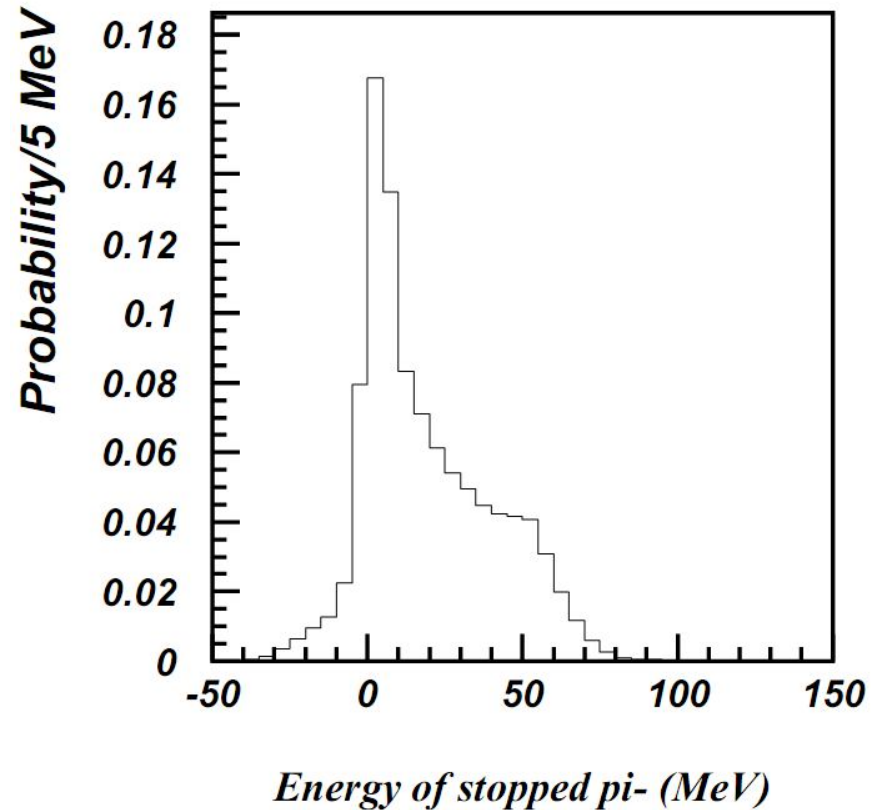




# Use target pattern recognition to isolate sample and estimate rejection power using simulation

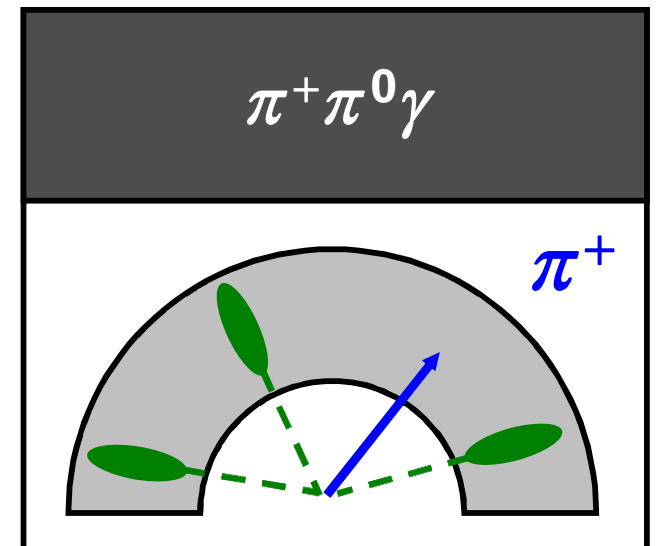
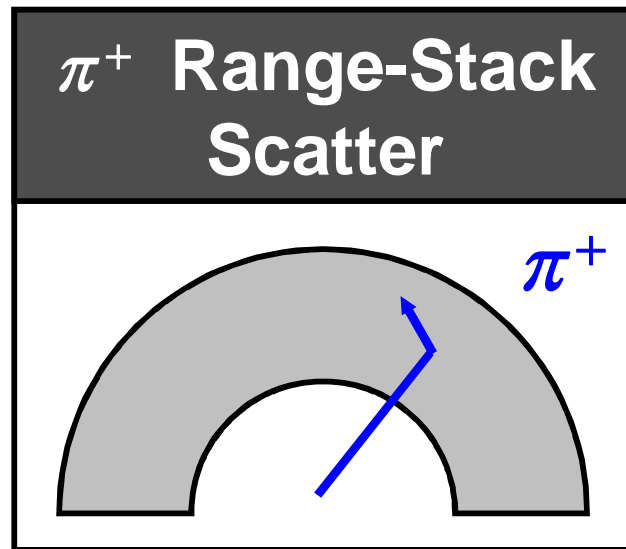
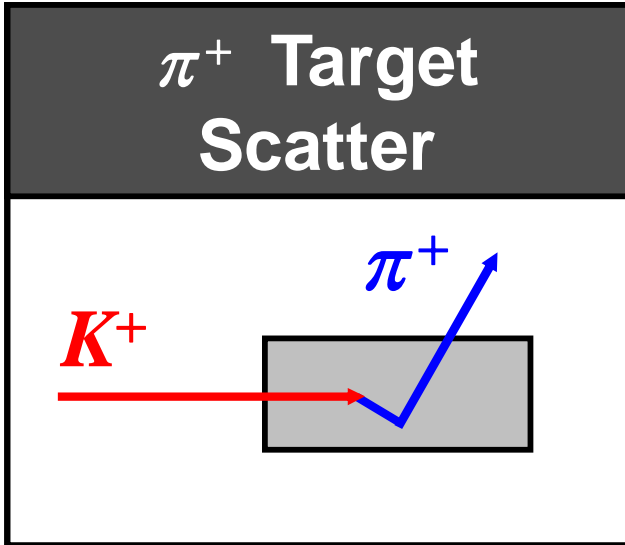


$K^+ \rightarrow \pi^+ \pi^- e^+ \nu$  sample is isolated  
using target pattern recognition



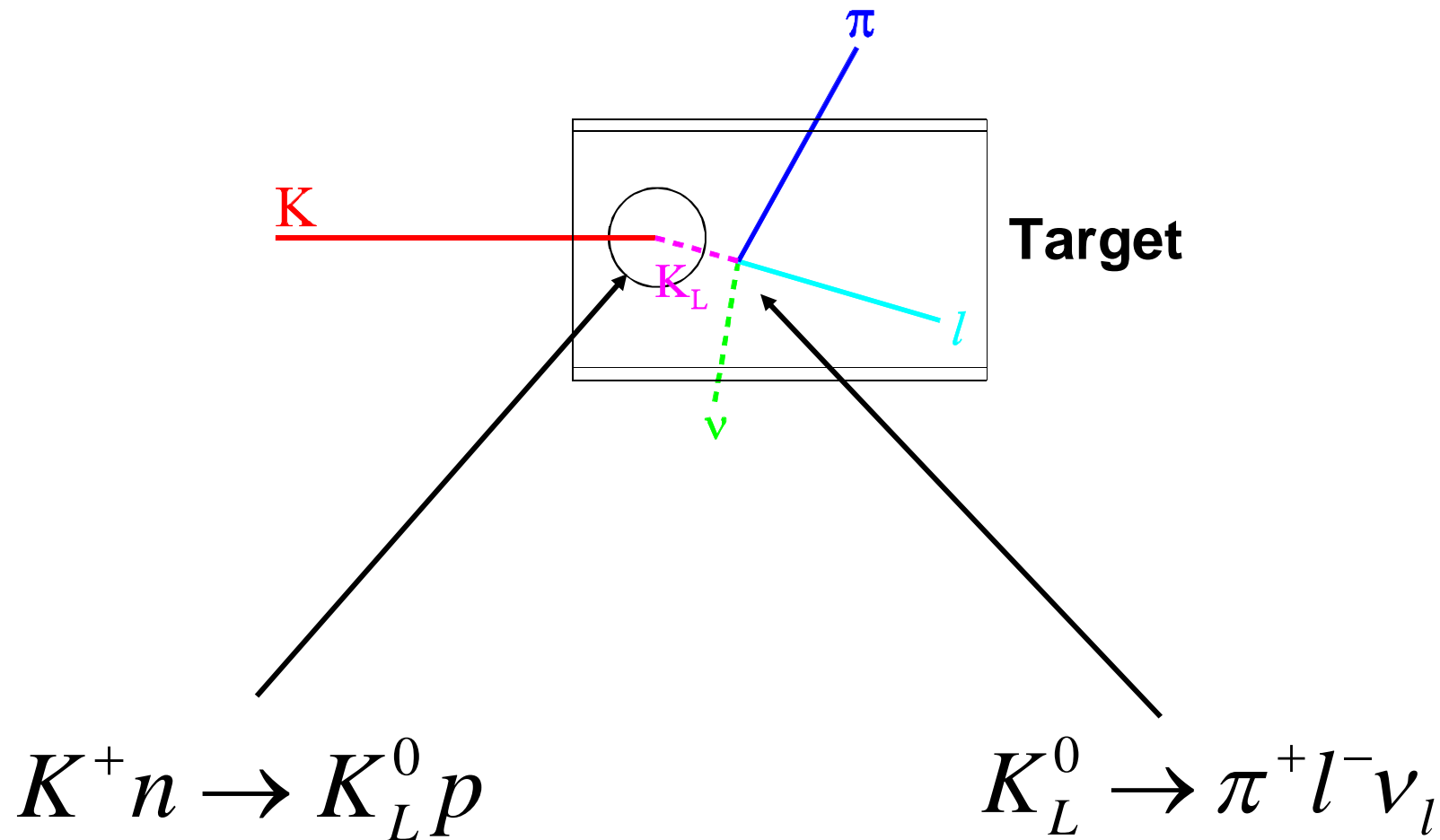
Estimate the rejection power of the target pattern recognition using simulated data supplemented by the measured  $\pi^-$  energy deposit in scintillator

In practice the three  $\pi^+\pi^0$  backgrounds have to be disentangled

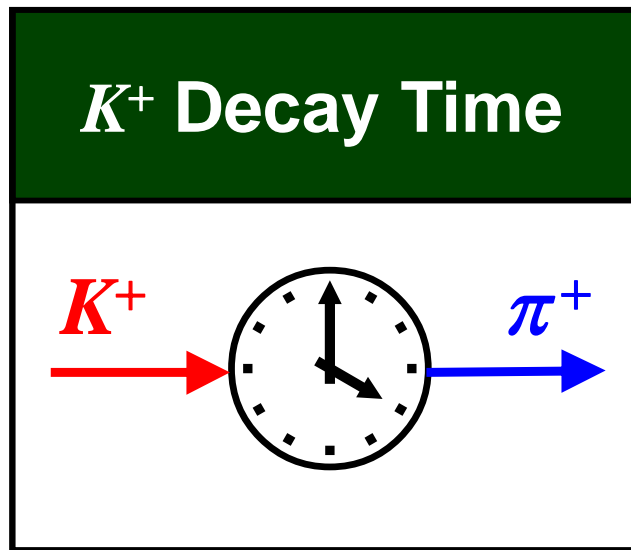


The  $\pi^+$  target scatter sample made by inverting the photon veto has contamination from  $\pi^+$  range-stack scatter and  $K^+ \rightarrow \pi^+ \pi^0 \gamma$  processes

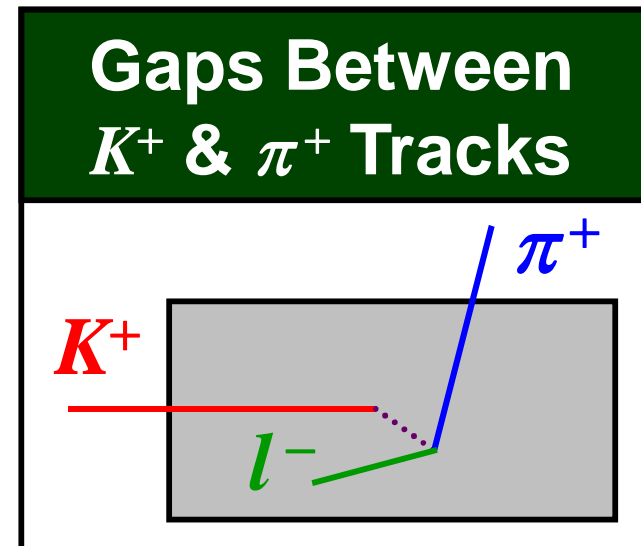
The charge exchange background is dominated by the neutral kaon decay  $K_L \rightarrow \pi^+ l^- \nu$



$K_S$  is suppressed by  $K^+$  decay time condition  
and  $K_L$  by gaps between the  $K^+$  and  $\pi^+$  tracks



$K_S$  lifetime is only 0.1 ns so  
the  $K^+$  decay time condition  
suppresses  $K_S$  decays



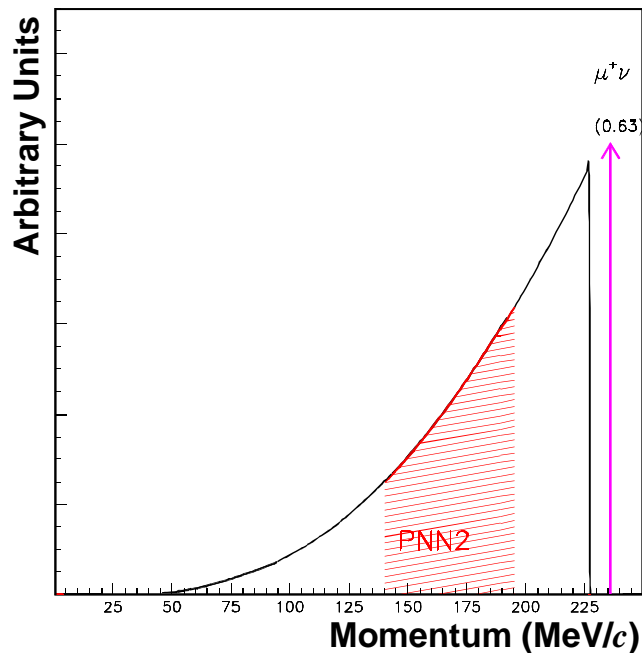
$K_L$  lifetime is 50 ns so target pattern  
recognition is used to identify gaps  
between the  $K^+$  and  $\pi^+$  tracks

Additional suppression is provided  
by detecting the negatively charged  
lepton

Due to kinematic constraints, the troublesome  $\mu^+$  decays are the multi-body ones

$$K^+ \rightarrow \mu^+ \nu_\mu$$

Not a big deal in  
the PNN2 region

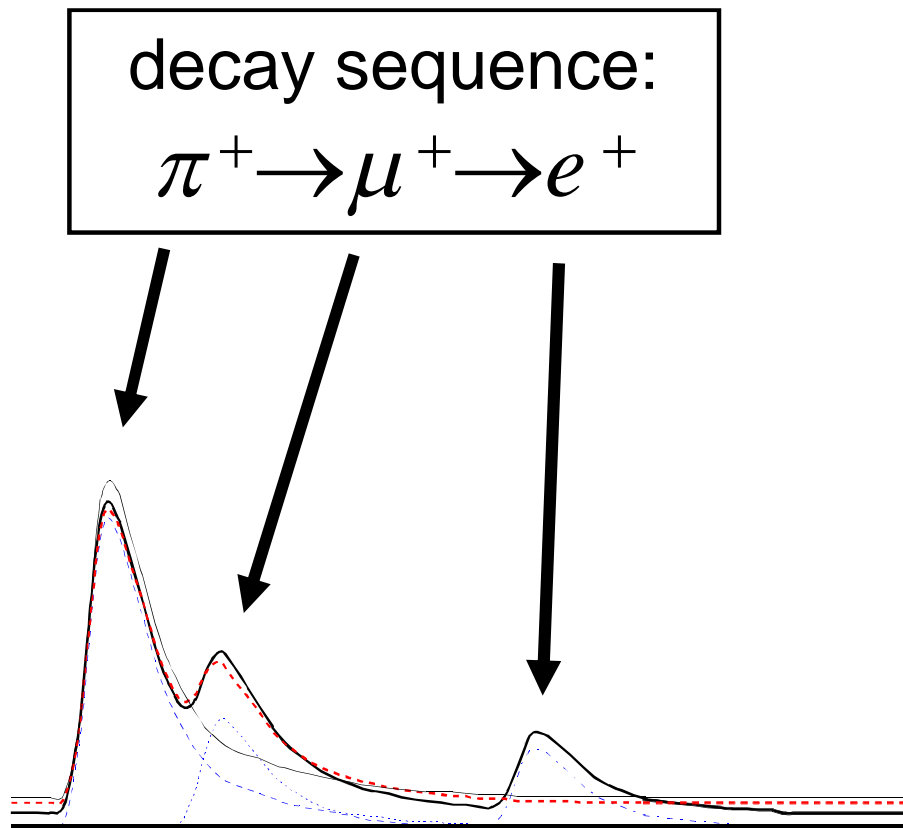


$$K^+ \rightarrow \mu^+ \nu_\mu \gamma$$

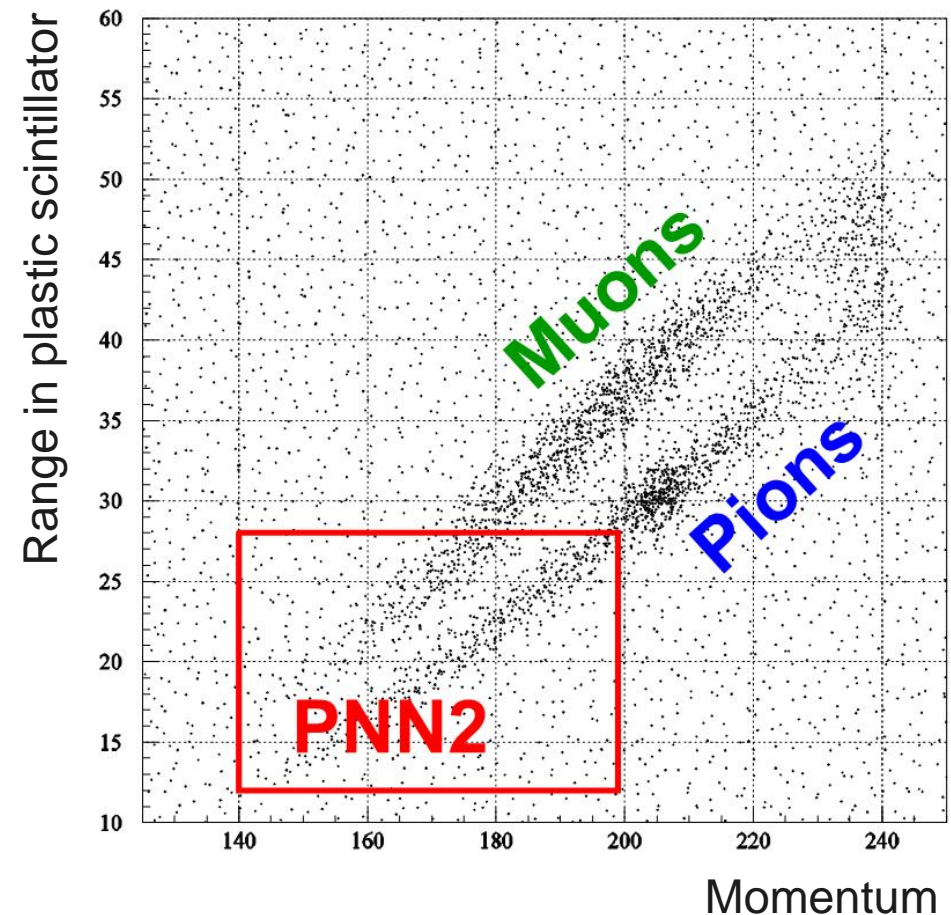


$$K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$$

# Muon processes are suppressed kinematically and by identification of the $\pi^+$ decay

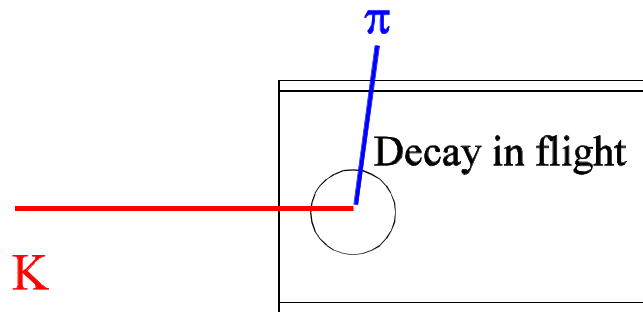


Pulse shape in the range-stack stopping counter

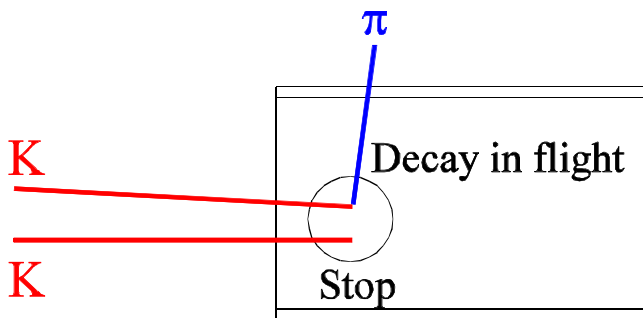
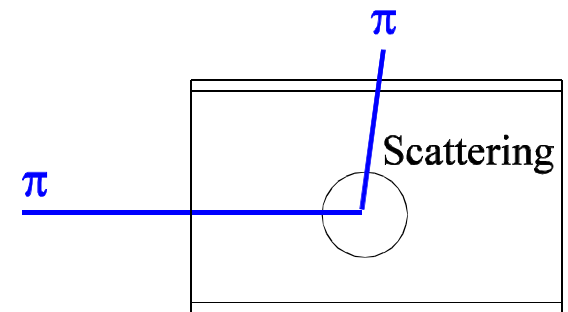
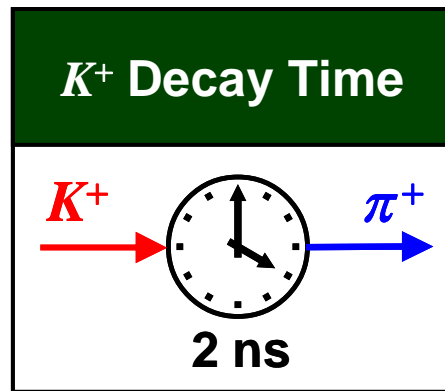


Muons have different kinematic signature in the detector than pions

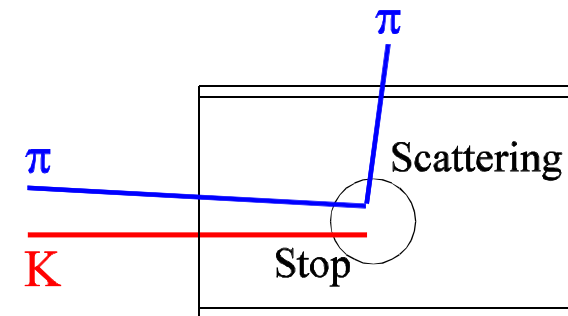
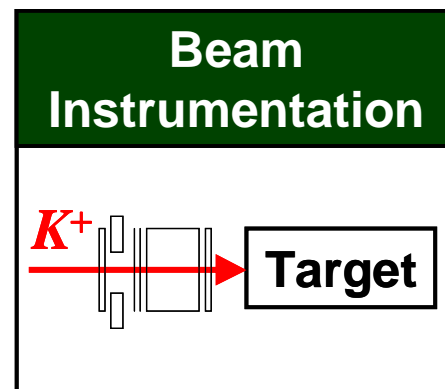
# Beam backgrounds come from events other than a single kaon decaying at rest in the target



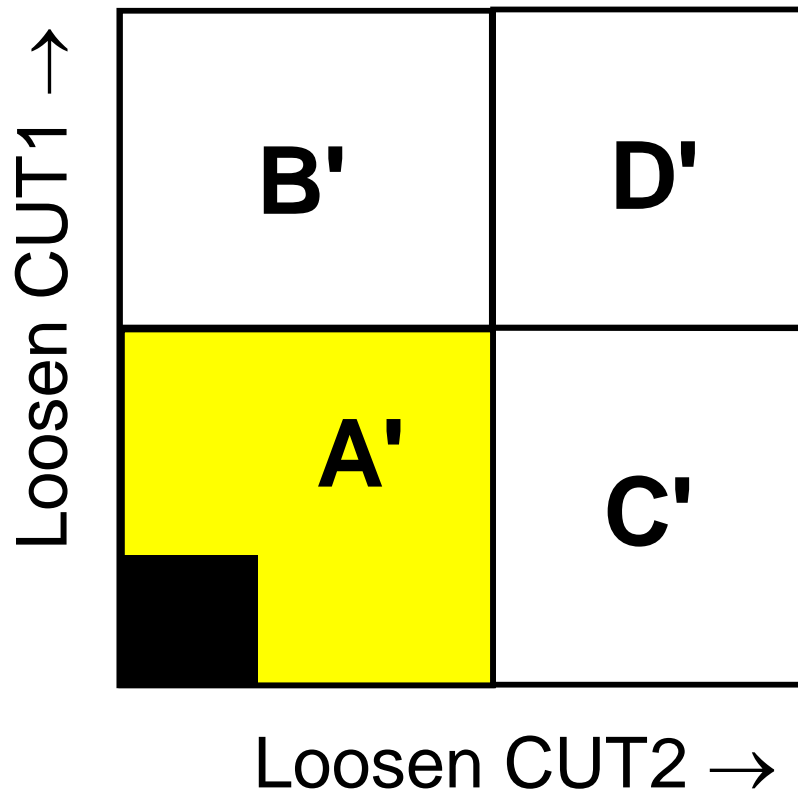
Single-beam



Double-beam



Outside-the-box studies compare background estimates to direct measurements just outside the signal region



Signal region is masked out;  
the background estimate and  
direct measurement for region A'  
are compared directly

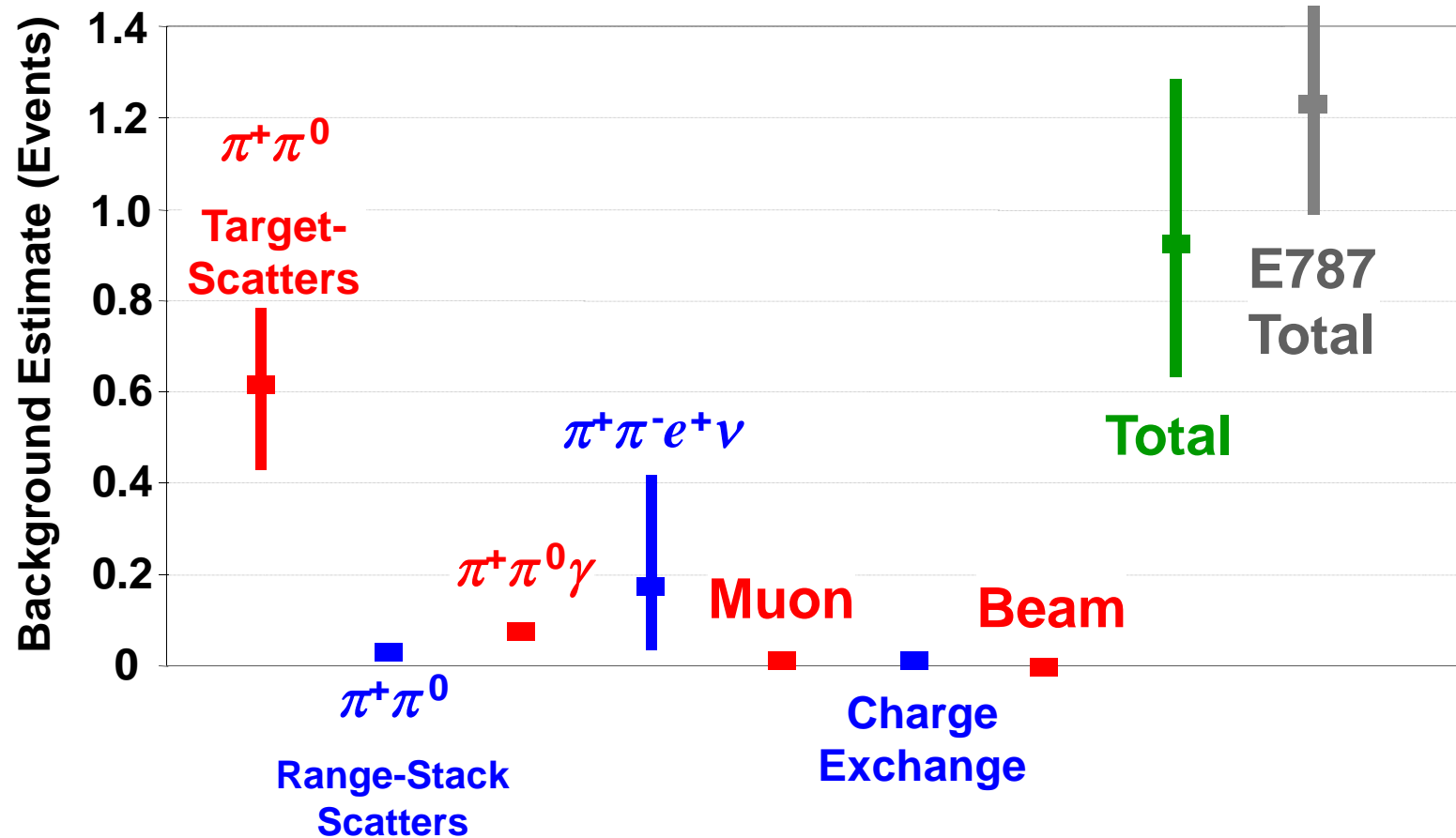
If CUT1 and CUT2 are uncorrelated,  
the two values will agree



The outside-the-box results demonstrate that the systematic uncertainties assigned to the backgrounds were reasonable

Region	$N_{\text{exp.}}$	$N_{\text{obs.}}$	$\mathcal{P}(N_{\text{obs.}}; N_{\text{exp.}})$	Combined
Target-scatter ID	$0.79^{+0.46}_{-0.51}$	0	0.45 [0.29,0.62]	N/A
Photon Veto 1	$9.09^{+1.53}_{-1.32}$	3	0.02 [0.01,0.05]	0.05 [0.02,0.14]
Photon Veto 2	$32.4^{+12.3}_{-8.1}$	34	0.61 [0.05,0.98]	0.14 [0.01,0.40]

Compared to the E787-PNN2 analysis, our total background was decreased by 24% and total acceptance increased by 63%

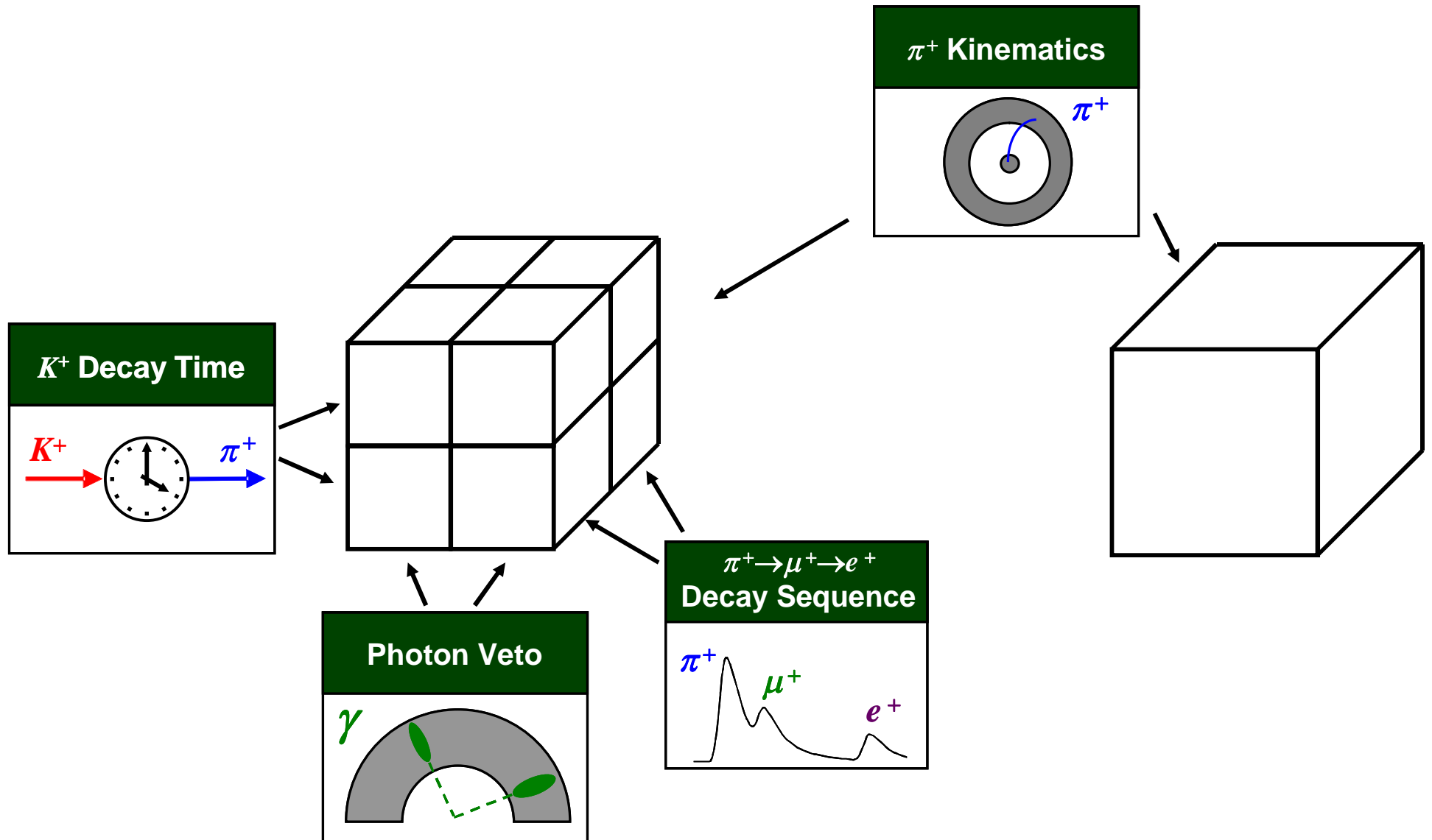


	E787-PNN2	This Analysis
Total kaons	$1.73 \times 10^{12}$	$1.70 \times 10^{12}$
Total acceptance	$0.84 \times 10^{-3}$	$1.37 \times 10^{-3}$

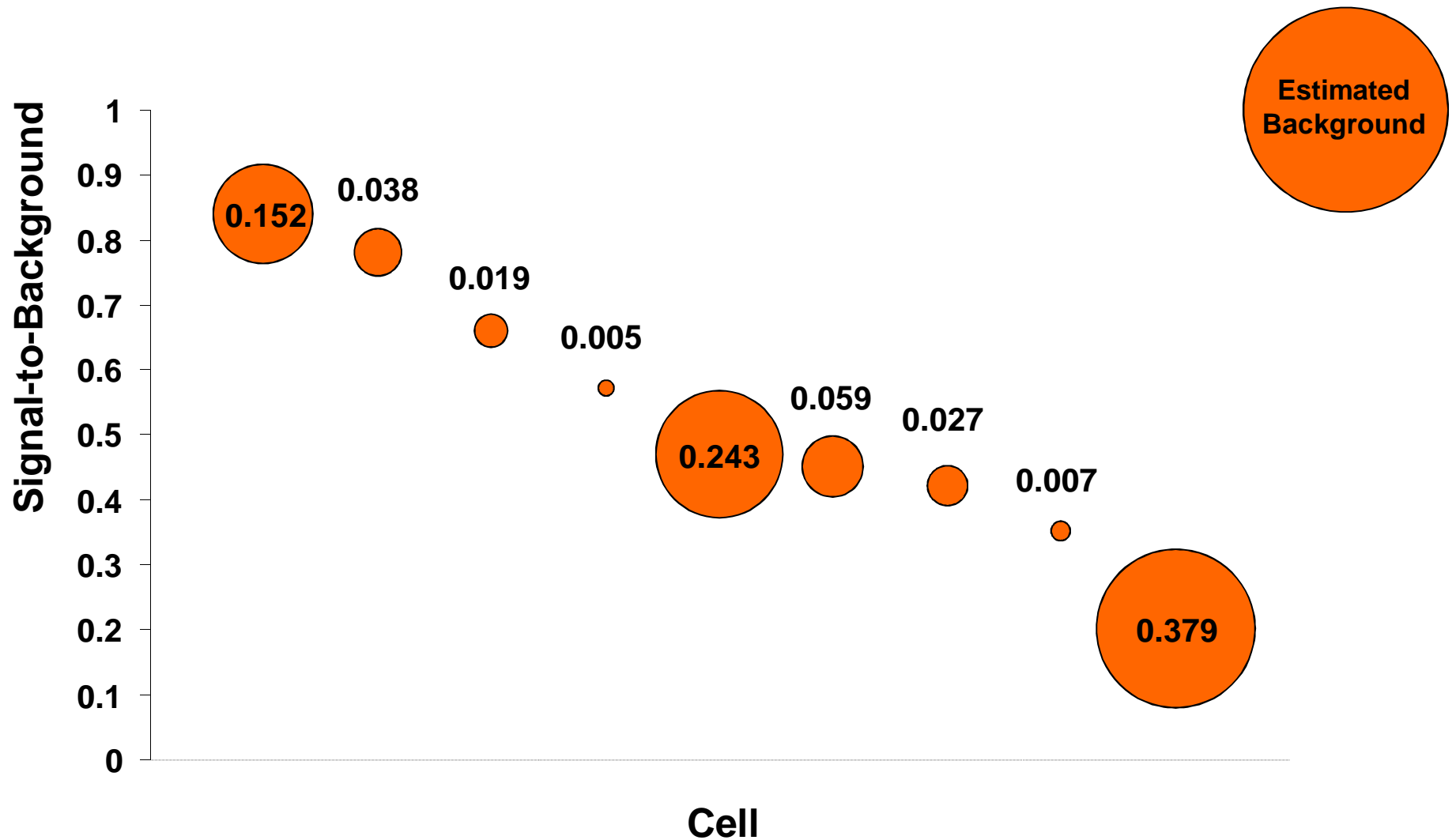
Only 20% of the approved beam time



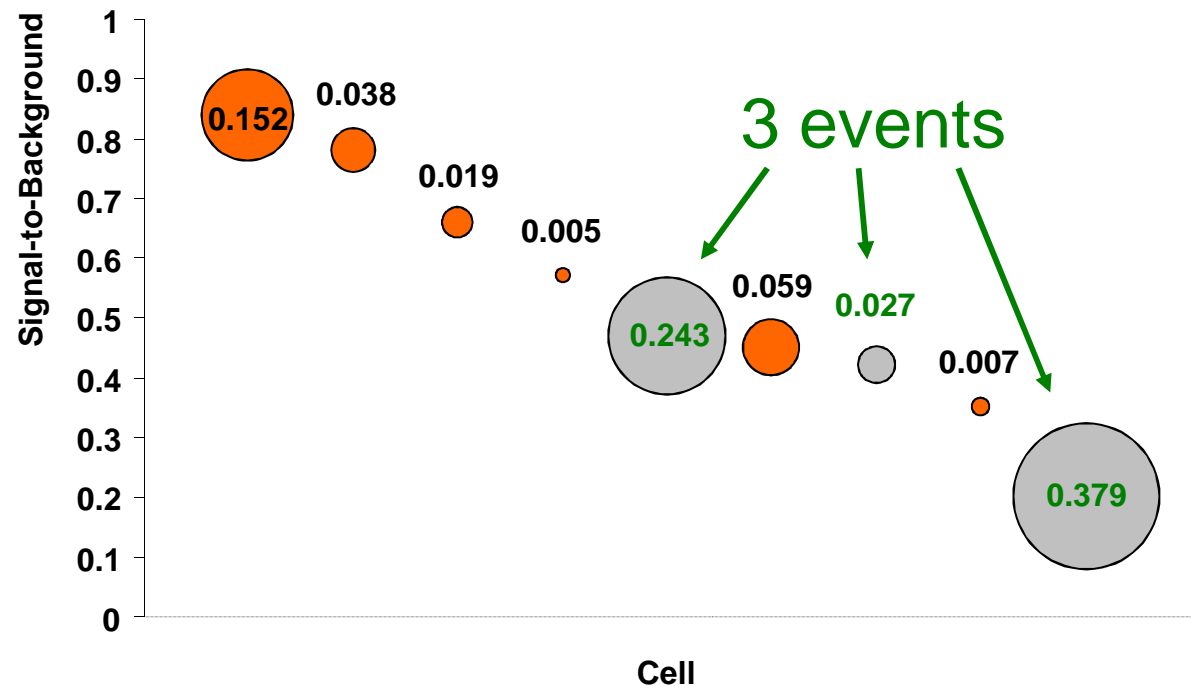
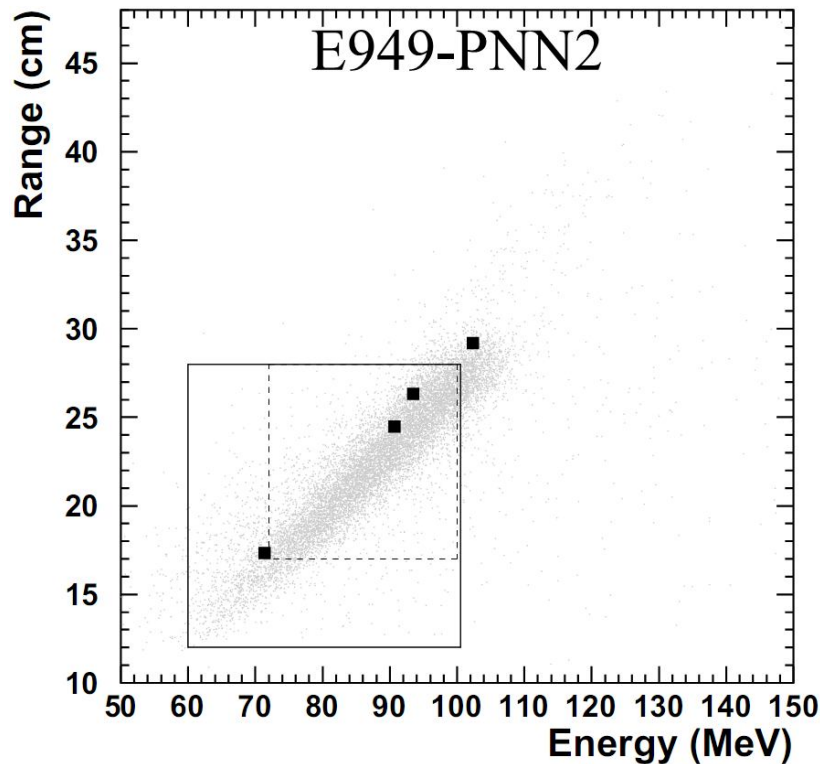
By further tightening four of the cuts, the signal region was divided into nine cells



The relative signal-to-background levels of the nine cells varied by about a factor of 4



...and three events were observed



The probability that all three events were due to background only is 3.7%

Measured branching ratio is  
 $B(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (7.89^{+9.26}_{-5.10}) \times 10^{-10}$